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CORRECTIONS AND EMENDATIONS

Contributors to Volume 52 have been invited to send corrections and emendations to be made in their paper, and the volume has been scanned with some care. Corrections and insertions are as follows:

Page 30, line 20, Rosebud *should be* boldface.
" 37, line 7 from bottom, author's name *should be* Abel.
" 52, Table 1, Cretaceous *should appear* opposite "Dakota sandstone".
" 177, Plate 1, in sections A–A′ and B–B′, *use* symbol for porphyry instead of that for basalt.
" 233, line 21, *for* 17, *read* 18; *for* 18, *read* 17.
" 437, line 19, for *Stimus,* read *Stibus.*
" 484, line 7 from bottom, after Lane, *insert* who believes it to be.
" 617, line 3, *for* microline, *read* microcline.
" 617, line 23, *for* contract, *read* contact.
" 625, line 5 from bottom, *insert* comma after Orijärvi.
" 646, Table 1, under "Point H", and on page 647, lines 10 and 11, *for* 30,000, *read* 3000; *for* 29,570, *read* 2570.
" 715, line 18 from bottom, *for* include, *read* intrude.
" 717, *after* common, *insert* enough.
" 741, lines 7 and 12 from bottom, *for* Table 6, *read* Table 7.
" 761, line 16, equation should read $T = (3/4\ k) + 3t$.
" " , line 20, equation should read $T = 3/4\ k$.

Bulletin
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Geological Society of America

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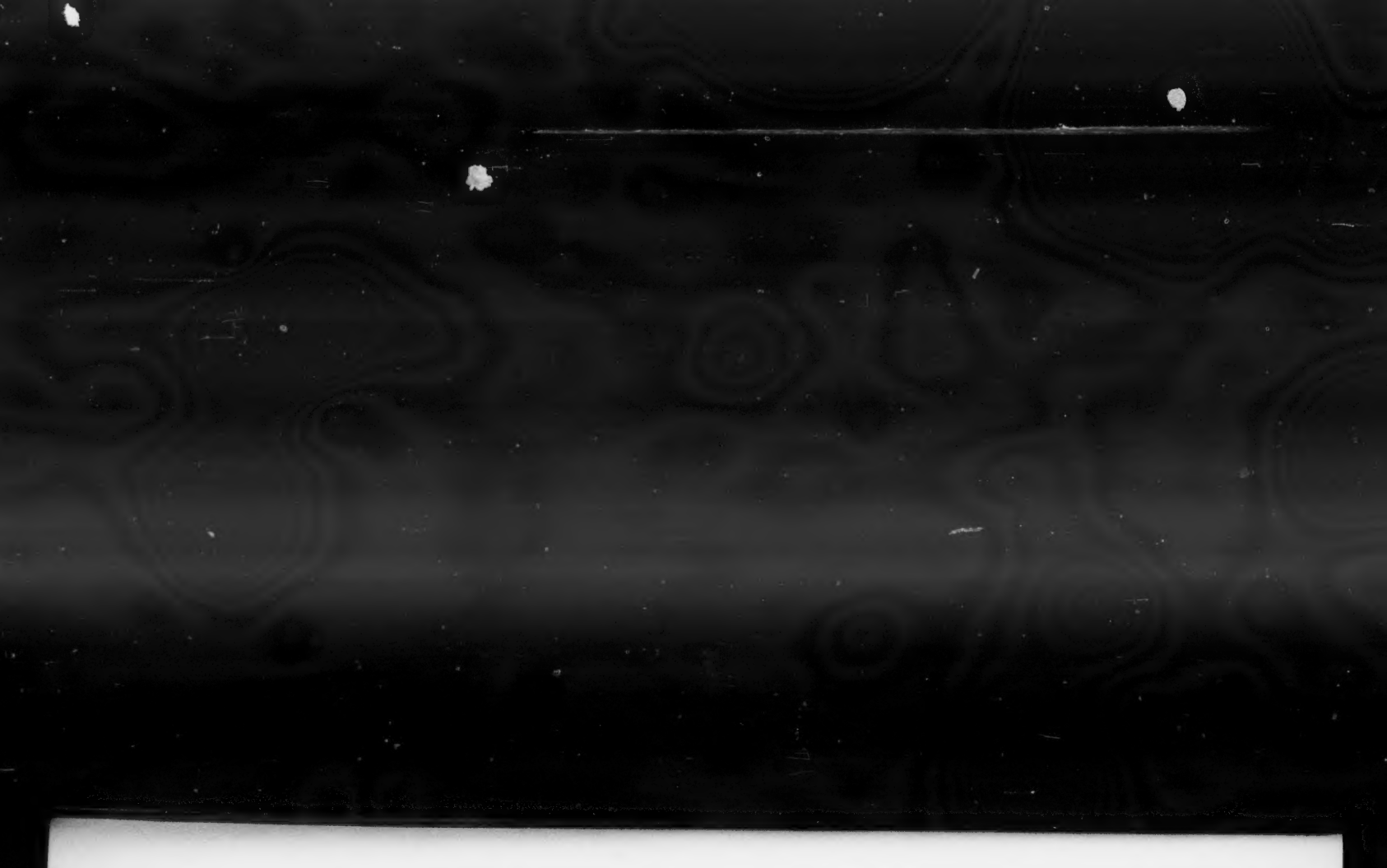

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PROVINCIAL AGES.
FAUNAL ZONES
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THREE FORKS
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PLIOCENE
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MANIX
TULARE FM.
SAN TIMOTEO L.F.
COSO MOUNTAINS L.F.
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SAN JOAQUIN L.F.
TEMBLOR FM.
TECUYA MEMB.
TICK CANYON FM.
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PHILLIPS RANCH L.F.
SESPE FORMATION
SOUTH MT. L.F.
KEW QUARRY L.F.
CALIF. TECH. LOC. 150
TAPO RANCH L.F.
POWAY CG.
TITUS CANYON FORMATION
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LEBO FM.
BEAR FM.
HELL CREEK FM.
PLEISTOCENE
MADISON VALLEY FM.
LEGISLATIVE TURNER LAKE BEDS
COVERED BY THE MADISON RIVER
JOHN DAY EQUIV.
FORT UNION SERIES
FORT UNION FM.
TULLOCK FM.
POLECAT BENCH FM.
CLARK FORK MEMBER
SILVER COULEE L.F.
ROCK BENCH L.F.
?
MANTUA LENTIL
LANCE FM.
LAST CABIN LYSITE EQUIV.
GRAY BULL MEMBER SAND
COULEE L.F.
INDIAN MEADOWS FM.
WIGGINS FM.
TEPEE TRAIL FM.
AYCROSS FM.
LOWER BRULE
CHADRON FM.
BATES HOLE L.F.
UINTA EQUIV. AT BEAVER DIVIDE AND BADWATER
GREEN COVE FM.
WIND RIVER FM.
LOST CABIN MEMBER LYSITE MEMBER
LANCE

CORRELATION CHART

NEBRASKA
EASTERN COLORADO
KANSAS
OKLAHOMA-ARKANSAS
NORTHWEST TEXAS
NEW MEXICO AND ADJOINING ARIZONA AND COLORADO
HONDURAS
MEXICO CITY REGION
TEXAS COASTAL PLAIN
LOUISIANA
FLORIDA
MARYLAND
NEW JERSEY
EUROPEAN AGES
NORTH AMERICAN PROVINCIAL AGES
PLEISTOCENE
ASTIAN
BLANCAN
PLAISANCIAN
HEMPHILLIAN
PONTIAN
CLARENDONIAN
SARMATIAN
BARSTOVIAN
TORTONIAN
HELVETIAN
HEMINGFORDIAN
BURDIGALIAN
AQUITANIAN
ARIKAREEAN
CHATTIAN
WHITNEYAN
STAMPIAN (RUPELIAN)
ORELLAN
SANNOISIAN (LATTORFIAN)
CHADRONIAN
LUDIAN
DUCHESNEAN
BARTONIAN
UINTAN
AUVERSIAN
LUTETIAN
BRIDGERIAN
CUISIAN (YPRESIAN)
SPARNACIAN
WASATCHIAN
THANETIAN
CLARKFORKIAN
TIFFANIAN
?
TORREJONIAN
?
DRAGONIAN
?
PUERCAN
UPPER CRETACEOUS
OGALLALA GROUP
SANTA FE FM.
GOLIAD SAND
OAKVILLE SS.
LAGARTO CLAY
CATAHOULA FORMATION
JUNIOR OIL CO. BEARD NO. 1 WELL
SHARK RIVER MARL
CANYON LARGO GROUP
TORREJON FORMATION
PUERCO FORMATION
OJO ALAMO FORMATION
MARTIN CANYON "BEDS"
CEDAR CREEK FACIES
HORSETAIL CREEK FACIES
WHITNEY MEMBER
ORELLA MEMBER
HUERFANO FM.
TIFFANY L.F.
LARGO L.F.
ALMAGRE L.F.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 52, PP. 1-48, 1 PL. JANUARY 1, 1941

NOMENCLATURE AND CORRELATION OF THE NORTH AMERICAN CONTINENTAL TERTIARY

(Report by Horace E. Wood, 2nd., *Chairman*, Ralph W. Chaney, John Clark, Edwin H. Colbert, Glenn L. Jepsen, John B. Reeside, Jr., and Chester Stock, *Committee*.)

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ABSTRACT

This report presents a provincial time scale for the North American continental Tertiary. It proposes a standardized terminology of purely temporal significance based on North American mammal-bearing units, of which the constituents are defined in terms of precisely analyzed faunas and the related stratigraphy. With such a nomenclature, exact information may now be conveyed without facing the continual dilemma between trying to conform to the European standard time scale or using American formation names as time units. The latter has been increasingly the practice in spite of inevitable ambiguities. In addition, it will be possible to discuss problems of relative age relationship and stratigraphic correlation without the distraction of endless controversies over epoch boundaries.

More than 300 significant rock and faunal units are defined, located, and delimited and, if necessary, discussed in the glossary. They have been analyzed in accordance with the most recent data afforded by field research and work on collections by the various specialists.

The correlation chart is in reality a graphic abstract, giving a bird's-eye view of the North American continental Tertiary as it is known to date. Tentative correlations with the European scale are added. The bibliography is selected for convenience rather than completeness.

INTRODUCTION

The justification for the technical terminology of any specialty is not to serve as a hog Latin by which initiates may mystify and exclude hoi polloi, but rather to be the means for recording and communicating with precision all facts and generalizations as they are established in that

particular field. If it becomes virtually impossible to convey the exact results obtained with any certainty of being correctly understood, it is clearly time either to modify or replace the outgrown terminology. Such a point has been reached by paleontologists dealing with North American fossil mammals and the deposits in which they occur. It is now possible to establish the correlation of these deposits more closely than can be indicated in words to another worker without the risk of dangerous ambiguity, cumbersome circumlocution, or both. For example, as things now stand, it would be necessary to say either, "these beds seem approximately of lower upper middle Eocene age, as currently understood by most North American vertebrate paleontologists", or else "these beds, although not referable to the Bridger formation, are about equivalent in age to Bridger C". The second, apparently simpler alternative, is actually the more dangerous, as transfer through one or two citations usually transforms this into "So-and-so identified an outlier of the Bridger formation in ——" (Montana, California, British Columbia, New Jersey, or whatever extremely improbable area the Bridger formation is thus extended into). The alleged widespread distribution of the Wasatch is a case in point.

This report is intended to cover all known mammal-bearing formations of the North American continental Tertiary, including Mexico, Central America, and the West Indies. It also includes marine formations which contain land mammals, a summary of Pleistocene mammalian occurrences, a cursory survey of certain uppermost Cretaceous formations, and some other formations which are closely associated stratigraphically with representatives of included categories. All temptations to expand this scope further have been resisted, as this would be beyond the function and knowledge of the committee and likely to result in perfunctory, derivative work. Necessarily, many of the conclusions reached are of the most tentative character, and their expression on the correlation chart (Pl. 1) is sometimes too positive, since it fails to indicate any shades of doubt or probability. In other cases, due to the size limitations of the chart, fine gradations of established opinion must be left unexpressed. It is earnestly requested that the committee be informed of omissions from, errors in, or new discoveries bearing on, this report, should a revised edition appear desirable in future.

It is to be hoped and expected that the local scale proposed in this report will, in future, be correlated step by step with the standard marine sequence; and if the proposed terminology should ever be abandoned as superfluous, due to increased knowledge, such abandonment would be a most satisfactory evidence of progress. A tacit provincial time scale has

already arisen, but its efficiency is seriously hampered by the confusing use of identical terms for rock units and for the time units which are implicitly but not explicitly generalized from them. It serves as the starting point for the formulation of the proposed terminology. The opportunity is also utilized to bring down to date, revaluate, and codify the stratigraphy of the mammal-bearing beds, in the tradition of such earlier summaries as those of Osborn and Matthew (1909), Simpson (1933), and Stirton (1936a). Although this will serve American workers primarily, it is clear that there are also European workers who would welcome a synthesis of the latest data. (Cf. Pilgrim, 1940.)

As this report has been a co-operative venture by the entire profession, full acknowledgment would list the majority of vertebrate paleontologists in the United States and Canada, as well as several dozen other workers. This co-operation has been so general that it is difficult to select any list of names, short of the full number. However, the Committee should certainly specifically thank the following: the U. S. Geological Survey, the Canadian Geological Survey, the Committee on Geologic Names and Correlations of the American Association of Petroleum Geologists, C. O. Dunbar, M. K. Elias, C. L. Gazin, J. T. Gregory, G. G. Simpson, R. A. Stirton, V. L. VanderHoof, R. W. Wilson, and A. E. Wood. The American Museum of Natural History has co-operated in various ways, particularly in providing the services of Mr. John Germann to draft the correlation chart. The personal familiarity of the chairman with most of the deposits considered has been greatly assisted by research grants made for other purposes by the New York Academy of Sciences, Washington Square College of New York University, and the American Philosophical Society.

HISTORY OF COMMITTEE

The original impetus for this report developed from a proposal to the December 1937 meeting of the Vertebrate Section of the Paleontological Society to set up a provincial time scale (Wood and Colbert, 1938). This was suggested, not as an attempt to secede from the standard international time scale, but to permit accurate and exact expression of the existing possibilities for correlation of mammal-bearing beds, without confusion with the less exact correlations possible between them and the marine sequence. Thus it might be possible to express as much as is demonstrable, without implying a further correlation which goes beyond the present bounds of reliable inference (as in calling the Uinta, "Bartonian", which may be more or less correct but certainly goes further than the known facts). It was obviously the desire of the meeting not to return to the practice (now largely abandoned by mammalian paleontologists)

of depending on faunal zones utilizing generic or specific names. After considerable discussion

"It was Resolved, that the chairman appoint a committee to canvass the possibilities and usefulness of a provincial North American Tertiary time-scale; this committee, after submitting such a tentative scale to members of the section and appropriate outside organizations, specifically the Committee on Geologic Names [of the U. S. Geological Survey] . . . and interested state surveys, shall then, if it sees fit, formally propose and publish such a provincial time scale" (Romer, 1938).

Accordingly, the Chairman of the Vertebrate Section, Dr. Walter Granger, appointed the following committee: Professor Ralph W. Chaney of the University of California, Dr. John Clark of the University of Colorado (now of the Carnegie Museum), Dr. Edwin H. Colbert of the American Museum of Natural History, Professor Glenn L. Jepsen of Princeton University, Dr. John B. Reeside, Jr., of the U. S. Geological Survey, Professor Chester Stock of the California Institute of Technology, and Professor Horace E. Wood, 2nd., of the University of Newark, Chairman.

A number of informal meetings were held with groups of available specialists, and discussions were carried on individually with other workers by the chairman and other members of the committee both personally and by mail. Some 50 interested individuals were consulted at this stage. On the basis of the opinions and criticisms expressed, a revised draft of a Tertiary continental time scale was submitted as a progress report to the 1938 meeting of the Vertebrate Section. Several especially difficult problems were placed before the section for informal vote. It was then resolved:

"That the report of the committee on a provincial North American Tertiary time-scale be accepted in principle as a preliminary report; that the life of the committee be extended for another year with instructions to complete the column, prepare faunal definitions of these time terms and a correlation chart showing their best understanding of the significance of the correlation of the North American Tertiary mammal-bearing beds in terms of this terminology, with instructions to consult such supposedly interested surveys, societies, and individuals as have not yet been consulted" (Romer, 1939).

In accordance with this resolution, 16 mimeographed pages and 2 offset correlation charts were mailed to more than 100 organizations and individuals, in advance of the 1939 meeting, as a trial report. Several dozen replies were received, almost all containing valuable criticisms and suggestions. After extended discussion at the 1939 meeting of the Vertebrate Section, it was voted

"that the present report be accepted as final, that the Committee be instructed to prepare it for publication, utilizing such constructive criticisms as shall have been received before the manuscript is in final form, and that the committee submit the report for publication in some appropriate medium" (Simpson, 1940).

The following report is, accordingly presented.

TERMINOLOGY

This report conforms to the recommendations of the joint committee on stratigraphic nomenclature (Ashley *et al.*, 1933), although full advantage is taken of permissive recommendations in giving provincial age names as subdivisions of epochs (*cf.* Article 24, and remarks (b)-(f), inclusive) and in using informal or semi-formal geographic names for local faunas or faunal zones. (*Cf.* Article 14, including remark (a), and Article 18.) The following recommendations of the joint report bear on the present report: Articles: 2, including (2)-(5), (b)-(d); 5, including (a)-(e); 6, including (a), (b), (d); 7, including (b)-(h), (j), (m)-(t); 8, including (a), (b); 9; 11, including (a)-(c); 12, including (a), (b); 13; 14; 15, including (b)-(e); 16, including (a)-(d); 17, including (c); 18; 23, including (a); 24, including (1)-(3), (b)-(f); 25.

Some minor deviations from approved standards are required by the space available in the correlation chart. Occasionally, such terms as formation, sandstone, member, and local fauna have been omitted, and a few self-explanatory abbreviations in the names themselves have been made. All these abbreviated names appear in full in the Glossary.

It seems desirable more clearly to distinguish time, rock, and faunal units than has generally been done in the past. As a basis for the time units, the standard section used by most vertebrate paleontologists working on the North American continental Tertiary has been modernized, and codified into a time scale by the addition of "ian", "an", or "n" to distinguish the time unit, an "age" in the limited but technically correct sense as defined by the International Geological Congress (Renevier, 1901, p. 196), *i.e.*, a fraction of an epoch, usually a third, sometimes a quarter or a fifth, from the rock unit—*i.e.*, formation, member, or "beds", or the local fauna, on which the age term is based. This does not follow the recommendation of the joint committee that "epoch" be used both for the epoch proper and for a fraction of an epoch (Ashley *et al.*, 1933, p. 445-446) but returns to the less ambiguous recommendation of the International Geological Congress, which, also, more nearly reflects general practice (Rutten, 1929, p. 199). Both the Congress report (Renevier, 1901, p. 202) and the joint report (Ashley *et al.*, 1933, p. 446) agree that divisions of this rank normally have only regional significance. The closest American analogues in current use are the provincial names for epochs or, better yet, the subdivisions of epochs (*e.g.*, Oriskanian) which are of exactly the scope of the ages here proposed (though they are not ordinarily designated as ages) and in the time terms for Pleistocene glacial "stages". These new terms are also roughly comparable in scope to the European Tertiary time terms, except that the former are frankly

provincial, whereas the latter are often considered as theoretically subject to universal extension. Although the supposed equivalence of the proposed terms to the epochs and the European ages and stages is indicated on the correlation chart and sometimes by inference in the text, the new terms are emphatically not defined in relation to either epochs or the European standard, but only as indicated below in the Definitions of Age Terms. (No attempt is made to show European equivalents for the North American early and middle Paleocene, since no fossil mammals of this age are known in Europe, and it is entirely speculative whether any part, and, if so, what part, of the Danian and Montian should be assigned to this time.) The same terms can also serve for the corresponding stages, *sensu stricto* (Renevier, 1901, p. 196), if any one wishes to use them in that sense; however, the committee believes that, unlike widespread marine deposits in which a stage may be a very real entity, a stage as applied to the more variable continental deposits is usually an abstraction, consisting simply of all the continental deposits dating from a given age. Nevertheless, there is no desire to oppose the use of these names for the corresponding stages, where such use seems desirable. Although the proposed terms are not regarded as available for extension beyond the limits of North America, since, if they were so extended, they would merely superfluously duplicate the standard succession, they apply to the whole North American continental Tertiary and not merely to the type areas on which the names are based. That is, they are meant to cover all of Tertiary time, without reference to whether each year, century, or millennium is represented by a known faunule or stratum. The type of each age necessarily belongs to it, and the sequence and approximate scopes of the ages are thus intended to be definitely fixed (barring new discoveries which should lead to radically different interpretations). However, the ages are not necessarily coextensive with their types, and the precise limits between successive ages are intended to be somewhat flexible and may presumably be modified in the light of later discoveries. Thus the Wasatchian age is more extensive than the known mammalian faunas of the type Wasatch and probably less extensive than the time equivalent of the entire Wasatch group in the type area. The Barstovian age includes units which may be older than any part of the Barstow formation, and are certainly older than any of the faunules now known from the Barstow. It is even probable that the uppermost part of the Hemingford group extends well beyond the Hemingfordian into the Barstovian, and unfossiliferous Bridger E, tentatively excluded from the Bridgerian, is supposed to be of early Uintan age. Such anomalies have been avoided where practicable.

In deference to standard practice elsewhere, faunal zones are included in the correlation chart, but the generic names employed, although probably the most suitable which are available, indicate the difficulties involved in correlating by generic faunal zones rather than by provincial ages. Thus they are exposed to all the vicissitudes of zoological nomenclature (which are quite irrelevant to stratigraphic problems) so that *Eohippus* and *Titanotherium* are no longer available, and *Oreodon* is doubtfully valid, in addition to being known from deposits both earlier and later than the *Oreodon* zone. *Plesippus* is of doubtful generic rank. *Amynodon, Teleodus,* and *Merychippus* occur in later zones than those to which they give their names, and *Monosaulax* perhaps occurs somewhat earlier.

The self-explanatory term "local fauna" is introduced for such well known units as Almagre, Blanco, Clarendon, and Tiffany, as well as for many poorly known local terms (such as Douglas Flat and Toluca) which have been called "beds", "horizon", "faunal zone", or locality. Local fauna seems to be the most exactly descriptive term, conforming to articles 16 and 18 of the joint report (Ashley *et al.*, 1933) and lacking necessary lithologic implications. Some of these units may later acquire definite stratigraphic significance as members or formations, but it seems preferable, for the present, especially because of frequent loose usage in the past, occasionally to underestimate, rather than consistently to overestimate, their claims to rank as lithologic units. On the other hand, the fact that various authors have called the Lost Cabin, for example, a "faunal zone" does not make it any less valid a lithologic unit—probably best considered a member rather than a formation. A similar criticism applies to the manner in which the criterion of "mapability" is only too frequently applied, as, for example, between the Lysite and Lost Cabin, which could be separately mapped on a scale of one mile to the inch, despite published statements to the contrary. (Parenthetically, the ability of a few people to map a unit is a more significant criterion of mapability than the inability of any given number of others to do so.)

The correlation chart largely follows standard practice. Known (but not inferred) unconformities are indicated by wavy lines, and known superposition above an unconformity by a double-headed arrow. Except in a few special cases, standard abbreviations are employed, local fauna being abbreviated into L. F. In a broad way, the section runs from west to east, but this arrangement is modified by the attempt to juxtapose related columnar sections. The European standard and the epochs are included for comparison, to show the correlations currently adopted by the committee and qualified specialists, but there is no intention or hope on the part of the committee of deciding, for example, where the Pliocene-Miocene boundary "really" is. The committee specifically disclaims any

supernatural sources of information regarding this or any other controversial problem. One of the incidental advantages of the proposed terminology is in making it easier to sidestep such controversies when they are irrelevant to the problem in hand, since Barstovian should be equally intelligible wherever the Pliocene-Miocene boundary might be drawn. The chart emphasizes the familiar fact that continental deposition during the Paleocene and Eocene was almost confined to the intermontane basins, whereas, during the later Tertiary, it took place largely on the Great Plains and Pacific Coast. However, various exceptional areas appear in which both time blocks are represented by deposition. Even in these cases, there is a sharp discontinuity in terms of time succession, lithology, or both, except in the Sespe formation and the Swift Current Creek-Cypress Hills succession, in which two cases only does continuity of depositional conditions bridge what is otherwise a striking geologic natural boundary.

DEFINITIONS OF AGE TERMS

The proposed terms appear in ascending geologic order. The fauna of each age may be classified under four headings: "index fossils", which are known only from deposits of the age in question; "first appearance" and "last appearance", applying only to North America, and, naturally, to the present state of knowledge; and "characteristic fossils", which are known to occur both in earlier and later deposits, but are, nevertheless, common for the age in question. Doubtfully referred or inadequately documented specimens which are the only basis for an extension in time range of a form which, otherwise, has a well-defined stratigraphic distribution are usually intentionally ignored. There is no attempt to give complete faunal lists, but rather to select the significant forms. Even should the ranges of certain of these forms be extended in future, the range in which the form is abundant is less likely to be affected. Usually the genera are used alone, but, where it seems desirable, specific names are also included.

Lance and equivalents—time term not proposed.
Faunal list of Lance mammals:
Multituberculata: *Cimolomys, Essonodon, Meniscoessus;*
Marsupialia: *Alphodon, Cimolestes, Delphodon, Diaphorodon, Didelphodon, Ectoconodon, Euangelistes, Nyssodon, Pediomys, Thlaeodon;*
Insectivora: *Batodon, Gypsonictops, Telacodon.*

Puercan age—new provincial time term, based on the Puerco formation of the San Juan Basin, northwestern New Mexico, type locality, Rio Puerco area; most typical and only fossiliferous exposures, the escarpment running from northwest of Ojo Alamo about 25 miles to Arroyo Eduardo, east of Kimbetoh.
Principal correlative: Mantua.

Index fossils: *Carsioptychus, Conacodon, Ectoconus, Eoconodon, Loxolophus, Onychodectes, Oxyacodon, Taeniolabis, Wortmania.*
First appearance: *Anisonchus,* Condylarthra, Creodonta, *Eucosmodon, Oxyclaenus,* Taeniodontia, Taligrada.

Dragonian age—new provincial time term, based on the Dragon local fauna in the North Horn "formation", Dragon Canyon, Emery County, Utah, principally from the western half of section 8, T. 19 S., R. 6 E.
Index fossil: *Dracoclaenus.*
First appearance: *Catopsalis, Haploconus,* mixodectids, *Periptychus, Ptilodus.*
Last appearance: *Oxyclaenus.*
Characteristic fossils: *Anisonchus, Ellipsodon.*

Torrejonian age—new provincial time term, based on the Torrejon formation of the San Juan Basin, New Mexico, type locality, the heads of Arroyo Torrejon; typical area runs from there northwest to Ojo Alamo, with additional, poorer localities scattered to the north almost to the Colorado line.
Principal correlatives: Lebo and Rock Bench.
Index fossils: *Conoryctes, Deltatherium, Mioclaenus, Mixodectes, Triisodon.*
First appearance: *Chriacus, Claenodon, Didymictis, Dissacus, Pantolambda, Psittacotherium, Tetraclaenodon.*
Last appearance: *Ellipsodon, Eucosmodon, Haploconus.*
Characteristic fossils: *Anisonchus, Periptychus, Ptilodus.*

Tiffanian age—new provincial time term, based on the Tiffany local fauna, often used in a more extended sense as a faunal level, northern rim of San Juan Basin, southwestern Colorado, typical area, Mason pocket, Sec. 20, T. 33 N., R. 6 W.
Principal correlatives: Bear Creek and Silver Coulee.
Index fossils: *Barylambda, Bathyopsoides, Labidolemur, Phenacodus grangeri, Sparactolambda, Titanoides.*
First appearance: *Palaeosinopa, Phenacodus, Plesiadapis, Probathyopsis,* Rodentia, *Thryptacodon.*
Last appearance: *Anisonchus, Claenodon, Leptacodon, Pantolambda, Tetraclaenodon.*
Characteristic fossil: *Ectypodus.*

Clarkforkian age—new provincial time term, based on the Clark Fork member (and faunal zone) of the Polecat Bench formation, type locality, scarp forming divide between Bighorn and Clark Fork basins and exposures near its base, Park County, Wyoming.
Index fossil: *Plesiadapis cookei.*
First appearance: *cf. Coryphodon, Ectocion, Esthonyx, Oxyaena.*
Last appearance: *Carpolestes, Plesiadapis.*
Characteristic fossils: *Didymictis, Ectypodus, Phenacodus, Probathyopsis, Thryptacodon.*

Wasatchian age—new provincial time term, based on at least the upper part of the Wasatch group of southwestern Wyoming (modified to Wasatchian series by C. R. Keyes). As a functional term, the typical areas and faunas must be regarded as those of the Bighorn and Wind River basins of Wyoming. The Wasatchian covers the time during which the faunas of the Sand Coulee, Gray Bull, Lysite and Lost Cabin were deposited. If technical justification for assigning the Lost Cabin to Wasatchian time is required, it is supplied by the discovery of the La Barge local fauna (*q.v.*, in the Glossary) in the type area of the Wasatch.

Principal additional correlatives: upper Canyon Largo and lower Huerfano.
Index fossils: *Ambloctonus, Anacodon, Diacodexis, Diacodon, Didelphodus, Heptodon, Homogalax ("Systemodon"), Hyracotherium ("Eohippus"), Lambdotherium, Meniscotherium, Pachyaena, Palaeonictis,* genus cf. *Paramys, Pelycodus, Prolimnocyon, Teilhardella.*
First appearance: *Anaptomorphus, Eotitanops, Hyopsodus, Miacis, Sinopa, Viverravus, Vulpavus.*
Last appearance: *Chriacus, Coryphodon, Didymictis, Dissacus, Ectocion, Ectypodus, Esthonyx,* Multituberculata, *Oxyaena, Palaeosinopa, Phenacodus, Probathyopsis, Psittacotherium.*

Bridgerian age—new provincial time term, based on the Bridger formation of southwestern Wyoming (or a redefinition of Bridgerian "series" of C. R. Keyes), or, more specifically, the time of deposition of Bridger A—D, inclusive, with the enclosed faunas.
Principal correlative: Washakie A with Bridger C + D.
Index fossils: *Apatemys, Helaletes, Helohyus, Homacodon, Hyrachyus affinis, H. princeps, Mysops, Orohippus, Palaeosyops, Patriofelis, Thinocyon, Tillomys, Tillotherium, Uintatherium.*
First appearance: *Harpagolestes, Limnocyon, Mesonyx, Notharctus, Paramys* (proper), *Sciuravus, Telmatherium.*
Last appearance: *Vulpavus.*
Characteristic fossils: *Hyopsodus, Hyrachyus, Miacis.*

Uintan age—new provincial time term, based on the Uinta formation of northern Utah, *i.e.,* the time of deposition of Uinta A—C, inclusive, with the included faunas.
Principal correlative: Washakie B with Uinta A+B.
Index fossils: *Achaenodon, Amynodon advenus, A. intermedius, Diplacodon, Dolichorhinus, Eobasileus, Epihippus, Leptotragulus, Mytonolagus, Oxyaenodon, Prodaphaenus, Protagriochoerus, Prothyracodon, Protitanotherium, Protoptychus, Protoreodon, Protylopus.*
First appearance: agriochoeres, *Amynodon,* Fissipedia, oreodonts, rabbits.
Last appearance: Dinocerata, *Harpagolestes, Hyopsodus, Hyrachyus, Ischyrotomus, Limnocyon,* Mesonychidae, *Mesonyx,* Oxyaenidae, *Notharctus, Paramys, Sciuravus, Telmatherium, Triplopus.*

Duchesnean age—new provincial time term, based on the Duchesne River formation of northeastern Utah.
Correlative: California Institute of Technology Locality 150 in the Sespe.
A faunal definition would be premature except to note the abundance of *Teleodus.* Hence the faunas are listed, separately.

Duchesne River fauna: *Amynodon, new species,* beyond *A. intermedius,* chalicothere, *Diplobunops*(?), *Duchesnehippus* (?*Epihippus*) *intermedius, Epitriplopus medius, Helohyus*(?), *Hessolestes ultimus, Heteraletes leotanus, Hyaenodon, Hyracodon primus, Leptomeryx minutus, Mesagriochoerus primus, Mesamynodon medius, Pentacemylus progressus, Poabromylus kayi, Protictops alticuspidens, Teleodus uintensis.*

Sespe locality 150 fauna: agriochoere, *Amynodontopsis bodei, Chumashius balchi, Hyaenodon vetus, Hyaenodon* (*Protohyaenodon*) *exiguus, Paramys* (Locality 151), *Pleurocyon* (*Simidectes*) *merriami, Proterixoides davisi, Protylopus*(?), *Pterodon californicus, Sespedectes singularis, Teleodus californicus, Triplopus*(?) *woodi.*

Duchesnean-Chadronian boundary: There is some reason to regard the Titus Canyon and Yoder faunas as covering part or all of the time interval which should still exist between the Duchesne River and Sespe 150 faunas, on the one hand, and the Pipestone Springs and Thompson Creek, on the other, which, again, are probably slightly older than the Chadron formation.

Titus Canyon fauna: *Protitanops curryi.*

Yoder fauna: *Ateleodon osborni, Brontops brachycephalus, Caenopus yoderensis, Hemipsalodon cooki, Hyaenodon horridus, Hyracodon ischyrolophus* (the specific validity and primitive character of *H. ischyrolophus* appear to be confirmed by an undescribed specimen in the collection of Mr. H. J. Cook), *Leptomeryx yoderi,* (?)*Mesohippus* (primitive), *Miacis matthewi, Subhyracodon woodi.*

Chadronian age—new provincial time term, based on the Chadron formation, type locality near Chadron, Nebraska; type area, northwestern Nebraska and southwestern South Dakota; includes the old term *"Titanotherium* beds," used in its most extended sense. It may also be defined, faunally, as the time during which *Mesohippus* and titanotheres co-existed.

Principal correlatives: Pipestone Springs, Cypress Hills.

Index fossils: *Allops, Brontotherium,* Cylindrodontidae, *Hyracodon priscidens, Megalagus brachyodon, Menodus, Palaeolagus temnodon, Titanotheriomys, Trigonias.*

First appearance: *Agriochoerus, Archaeotherium, Daphaenus, Dinictis, Hoplophoneus, Ictops, Metamynodon, Oreodon, Palaeolagus,* (?)*Poebrotherium, Pseudocynodictis.*

Last appearance: Brontotheriidae (largest forms, with largest horns), *Brontops.*

Characteristic fossils: *Hyaenodon, Leptomeryx, Mesohippus, Subhyracodon.*

Orellan age—new provincial time term, based on the Orella member of the Brule formation, type locality, Orella, northwestern Nebraska, type area, northwestern Nebraska, southwestern South Dakota and eastern Wyoming; includes the old term, *"Oreodon* beds," used in the most extended sense.

Principal correlatives: Cook Ranch and other scattered Montana deposits.

Index fossils: *Hoplophoneus primaevus, Hyracodon arcidens, Metamynodon planifrons, Poëbrotherium*(?), *Subhyracodon occidentalis.*

First appearance: *Eporeodon, Eumys, Hyracodon nebrascensis, Ischyromys, Palaeolagus haydeni.*

Last appearance: *Metamynodon, Oreodon, Poëbrotherium.*

Characteristic fossils: *Archaeotherium, Hydracodon, Leptomeryx, Megalagus, Subhyracodon, Stylemys.*

Whitneyan age—new provincial time term, based on the Whitney member of the Brule formation, type locality, Whitney, northwestern Nebraska; type area, northwestern Nebraska, southwestern South Dakota and eastern Wyoming; includes the old term, *"Protoceras-Leptauchenia* beds" used in the most extended sense.

Correlative: White Butte.

Index fossils: *Protoceras, Subhyracodon tridactylus.*

First appearance: Castoridae, *Leptauchenia, Miohippus.*

Last appearance: *Agriochoerus, Archaeotherium, Hyracodon, Mesohippus, Palaeolagus, Pseudocynodictis, Subhyracodon.*

Characteristic fossils: *Eporeodon, Leptomeryx.*

Arikareean age—new provincial time term, based on Arikaree group of western Nebraska, Agate being most typical locality, with the limits as redefined by Schultz (1938), but including the Rosebud. (*Cf.* Lugn, 1939b.)

Principal correlative: John Day (in part).

Index fossils: Daemonhelix, *Daphoenodon, Diceratherium, Dinohyus,* Entoptychinae, *Oxydactylus, Promerycochoerus, Stenomylus, Syndyoceras, Temnocyon.*
First appearance: *Anchitherium, Blastomeryx, Cyclopidius, Desmathyus, Merychyus, Mesoreodon, Moropus, Mylagaulus, Parahippus, Ticholeptus.*
Last appearance: entelodonts, *Eporeodon, Leptauchenia, Miohippus, Nimravus, Nothocyon, Palaeocastor.*

Hemingfordian age—new provincial time term, based on the Hemingford group, including the Marsland and, especially, the limited or lower Sheep Creek fauna (Cook and Cook, 1933, p. 38-40), and not on the formation limits as extended upward (Lugn, 1939b).
Correlative: Hawthorn.
First appearance: *Alticamelus, Amphicyon, Aphelops, Archaeohippus, Hypohippus, Merychippus, Merycodus, Pronomotherium, Protolabis, Tomarctus.*
Characteristic fossils: *Blastomeryx, Cyclopidius, Cynodesmus, Merychyus, Merycochoerus, Mylagaulus, Parahippus.*

Barstovian age—new provincial time term, based on the Barstow formation, San Bernardino County, California, and specifically on the fossiliferous tuff member in the Barstow syncline and its fauna.
Principal correlatives: Pawnee Creek, Deep River, Virgin Valley, Mascall.
Index fossils: *Amblycastor, Dyseohyus fricki, Hemicyon, Monosaulax, Peridiomys.*
First appearance: *Aelurodon, Calippus, Hypolagus,* Proboscidea, *Prosthennops, Teleoceras.*
Last appearance: *Archaeohippus, Parahippus.*
Characteristic fossils: *Alticamelus, Amphicyon, Aphelops, Blastomeryx, Cynodesmus, Hypohippus, Merychippus, Merycochoerus, Merycodus, Mylagaulus, Procamelus, Ticholeptus.*

Clarendonian age—new provincial time term, based on the Clarendon local fauna (and member?), near Clarendon, Donley County, Panhandle of Texas.
Principal correlatives: Burge, Big Spring Canyon, Fish Lake Valley, Ricardo.
Index fossils: *Eucastor, Megahippus, Synthetoceras.*
First appearance: *Bassariscus, Hipparion* (S. S.) *Megatylopus, Nannippus, Neohipparion, Pliauchenia, Pliohippus, Serridentinus, Sphenophalos.*
Last appearance: *Aelurodon, Alticamelus, Amphicyon, Calippus, Cynodesmus, Hypohippus, Merychippus, Merycodus, Metoreodon,* oreodonts (of which stratigraphic position can be considered certain), *Pliocyon, Procamelus.*
Characteristic fossils: *Aphelops, Mylagaulus, Osteoborus, Prosthennops, Teleoceras.*

Hemphillian age—new provincial time term, based on the Hemphill member of the Ogallala, which includes both the Hemphill local fauna from the Coffee Ranch Quarry and the Higgins local fauna, Hemphill County, Panhandle of Texas.
Principal correlatives: Edson, Feldt Ranch, Wray, Thousand Creek, Rattlesnake.
Index fossils: *Agriotherium, Dipoides, Ilingoceros, Plesiogulo.*
First appearance: ground sloths, *Lutravus, Machairodus, Taxidea.*
Last appearance: *Aphelops, Blastomeryx, Mylagaulus, Osteoborus, Pliauchenia. Pliohippus, Prosthennops,* rhinoceroses, *Sphenophalos, Teleoceras.*
Characteristic fossils: *Hypolagus, Megatylopus, Nannippus, Neohipparion.*

Blancan age—new provincial time term, based on the local fauna at "Mt. Blanco" and the adjoining draws, near the "old rock house," north of Crawfish Draw, Crosby County, Panhandle of Texas.

Principal correlatives: Rexroad, Benson, Hagerman.
Index fossils: *Borophagus, Ceratomeryx, Ischyrosmilus, Plesippus.*
First appearance: *Camelops, Canis, Cervus, Felis,* glyptodonts, hystricomorphs, many extant genera, especially of rodents, *Lutra, Mimomys,* myomorphs first predominate over sciuromorphs, *Megalonyx, Odocoileus, Paramylodon, Platygonus, Tanupolama.*
Last appearance: *Anancus, Lutravus, Megatylopus, Nannippus, ?Neohipparion.*
Characteristic fossil: *Hypolagus.*

Characteristic **Pleistocene** mammals: *Antilocapra, Aplodontia, Archidiskodon, Arctodus, Bison, Blarina, Boötherium, Boreostracon, Camelops, Canis, C. dirus, "Capromeryx" minor, Castor, Castoroides, Cervalces, Cervus, Chlamytherium, Citellus, Cynomys, Didelphis, Dipodomys, Equus, Erethizon, Euarctos, Euceratherium, Felis, Felis atrox, Geomys, Gulo, Holmesina, Homo?, Hydrochoerus, Lepus, Lutra, Lynx, Mammonteus, Marmota, Martes, Mastodon, Megalonyx, Megatherium, Mephitis, Microtus, Mimomys, Mustela, Mylohyus, Neochoerus, Neotoma, Nothrotherium, Ochotona, Odocoileus, Ondatra, Oreamnos, Otospermophilus, Ovibos, Ovis, Paramylodon, Parelephas, Perognathus, Peromyscus, Platygonus, Preptoceras, Procyon, Rangifer, Sciurus, Smilodon, Sorex, Spilogale, Stegomastodon, Sylvilagus, Symbos, Tagassu, Tamias, Tanupolama, Tapirus, Taxidea, Tetrameryx, Thomomys, Tremarctotherium, Urocyon, Vulpes, Zapus.*

GLOSSARY

This index of 349 terms associated with occurrences of Cenozoic land mammals in North America is as condensed as clarity warrants. All important terms appear on the chart, and what are otherwise occurrences of quite minor significance may appear on the chart when they are of correlative value, or when they may be fitted into otherwise unoccupied spaces. When minor, obsolete, or obsolescent terms are included in the glossary only, they are marked by a footnote. Some fairly important Pleistocene occurrences are omitted for convenience, and a very few units treated by Simpson (1933) or Stirton (1936a) have been considered too insignificant for mention.

The committee indicates whether it considers that each name actually applies to an age, a series, a formation, a member, or a local fauna, irrespective of whether this opinion conforms to previous published usage. Explanations of proposed innovations are kept brief. Often, a term first used informally to designate a locality or local fauna has gradually become recognized as a member or formation name without any definitely determinable date for the transition in viewpoint. The joint report (Ashley *et al.*, 1933, articles 8 and 9) condemns this for the future, but it is not retroactive.

Alachua formation, Hemphillian, a narrow north-south band, especially in Alachua, Levy, and Marion counties, Florida (Simpson, 1933; Stirton, 1936a; Wilmarth, 1938).

Almagre local fauna and faunal zone, doubtfully definable as a member and certainly not yet so defined, of Canyon Largo group (usually called San Juan Wasatch),

mid-Wasatchian of Rio Arriba County, northwestern New Mexico (Simpson, 1933; Wilmarth, 1938).

Almy formation of Wasatch group, southwestern Wyoming, especially Uinta County, very tentatively considered middle Paleocene (Nace, 1936, p. 146-148; Simpson, 1933, p. 114; Wilmarth, 1938).

[1]**Alturas** formation, late Clarendonian of Modoc County, northeastern California (Stirton, 1936a; Wilmarth, 1938).

American Falls lake beds, Pleistocene (probably early) of Power County, Idaho (Hay, 1927, p. 263-264; Stearns, Crandall, and Steward, 1938, p. 69-71, Pl. VI; Wilmarth, 1938).

[1]**Anguilla** local fauna, recent and/or late Pleistocene, Anguilla, British Virgin Islands, West Indies (Cope, 1883) also St. Martin (Schreuder, 1923), preoccupied as a geographic term. (*Cf.* Wilmarth, 1938.)

Arikaree group, Arikareean, formerly considered a formation, of western Nebraska and adjoining states; includes Rosebud (Cook and Cook, 1933, p. 28-37, 44; Lugn, 1939b; Simpson, 1933; Wilmarth, 1938).

Arikareean age, new provincial term proposed in this report.

Ash Hollow formation, principally Hemphillian, Nebraska, contains Minnechaduza (Valentine) local fauna, near base (Lugn, 1939b, p. 1258-1264).

"Auriferous gravels," loose term for deposits of varied age (Cretaceous to Pleistocene) on west slopes of Sierra Nevada Mountains, California (Wilmarth, 1938).

[1]**Axtel** local fauna, Hemphillian, Randall County, Texas (Johnston, 1939).

Aycross formation, Bridgerian, northwestern Fremont County, Wyoming (Love, 1939, p. 66-73).

Barstovian age, new provincial term proposed in this report.

Barstow formation, Barstovian, San Bernardino County, California (Baker, 1911; Merriam, 1915; 1919; Simpson, 1933; Wilmarth, 1938).

Bates Hole local fauna in Chadron formation, Chadronian, Natrona County, Wyoming (Simpson, 1933, p. 115; Wilmarth, 1938).

Bautista formation, Pleistocene, western Riverside County, California (Wilmarth, 1938).

Bear formation or member of (?)Fort Union, perhaps of Puercan age, Sweetgrass and Wheatland counties, Montana (Simpson, 1937, p. 14-20).

Bear Creek local fauna in Fort Union, Tiffanian, apparently preoccupied as a geographic term, Carbon County, Montana (Simpson, 1933).

Bear River formation, Upper Cretaceous of southwestern Wyoming (Nace, 1936, p. 6-9; Wilmarth, 1938).

Beaumont clay, late Pleistocene formation, Texas coastal plain (Wilmarth, 1938).

[1]**Beaver** local fauna in Ogallala, Beaver County, Oklahoma; term preoccupied (*cf.* Wilmarth, 1938); *see* Laverne (Stirton, 1936a).

[1] Indicates omission from the correlation chart.

Beaver Divide conglomerate, member of Chadron formation, Fremont and Sweetwater counties, Wyoming (Nace, 1939, especially p. 31-34).

[1]**Beecher Island** local fauna in Ogallala, Yuma County, Colorado; term preoccupied (*cf.* Wilmarth, 1938); *see* Wray (Stirton, 1936a).

Benson local fauna in San Pedro Valley formation, Blancan, preoccupied as a geographic term (*cf.* Wilmarth, 1938), Cochise County, Arizona (Simpson, 1933; Stirton, 1936a).

Bidahochi formation, late Cenozoic of northeastern Arizona (Wilmarth, 1938).

[1]**Bigbone Lick** local fauna, late Pleistocene, Boone County, Kentucky, first vertebrate fossil field discovered in North America (Hay, 1923, p. 401-404).

"Bighorn Wasatch," best known early Wasatchian, a classical formation which at present lacks any valid name; Van Houten will shortly name it the [1]Willwood formation (Simpson, 1933, p. 114).

Big Spring Canyon local fauna in (?) Little White River formation, or in Ogallala, in a geographically extended sense, Clarendonian, Bennett County, South Dakota (Stirton, 1936a).

Bijou Hills local fauna in(?) Ogallala, in a geographically extended sense, Barstovian, Brule County, South Dakota (Leidy, 1854; 1856; Hayden, 1857).

Black Hawk Ranch local fauna in Siesta formation, Clarendonian, Contra Costa County, California (Richey, 1938).

Black's Fork member of Bridger, early Bridgerian, southwestern Wyoming (Wilmarth, 1938).

Blancan age, new provincial term proposed in this report.

Blanco local fauna in Ogallala (not a valid formation, nor yet demonstrated to be a member). The typical locality should be regarded as restricted by usage to "Mt. Blanco" and the adjoining draws near Crawfish Canyon, Crosby County, northwestern Texas (Simpson, 1933; Stirton, 1936a; Wilmarth, 1938).

Bone Valley gravel, a Hemphillian formation, Polk and Hillsborough counties, Florida (Simpson, 1933; Stirton, 1936a; Wilmarth, 1938).

Box Butte, for the present best considered the upper member of the Sheep Creek formation, Barstovian, Box Butte County, Nebraska, mammalian fauna still undescribed (Cady, 1940).

[1]**Bozeman** "lake beds," loose term for the entire middle and late Cenozoic section northwest of Yellowstone Park in Gallatin and Broadwater counties, Montana, including beds ranging in age from early Chadronian to Pleistocene and devoid of lacustrine deposits (except the *Leuciscus turneri* lake beds). *See* the Three Forks column on the correlation chart (Wilmarth, 1938).

Bridger formation, Bridgerian, southwestern Wyoming, and narrow adjoining fringe in Utah. There is no positive evidence for correlating any deposits in the Uinta Basin (except part of the Green River) with any part of the Bridger (excluding the Washakie, *q.v.*), and only the unfossiliferous Bridger "E" may, or may not, be equivalent to some portion of the Uinta, *q.v.* (Nace, 1936, p. 209-229; Simpson, 1933; Wilmarth, 1938).

Bridgerian age, new provincial time term as defined in this report, but *cf.* Keyes' Bridgerian series (Wilmarth, 1938).

Broadwater local fauna, early Pleistocene, Morrill County, Nebraska (Barbour and Schultz, 1937).

Browns Park formation, Barstovian, principally Moffat County, Colorado (Simpson, 1933; Wilmarth, 1938).

Brule formation, Orellan and Whitneyan, South Dakota, Nebraska, Wyoming, Colorado and North Dakota (Simpson, 1933; Wilmarth, 1938).

Burge local fauna, Clarendonian, Cherry County, Nebraska (McGrew, 1938; Stirton, 1936a; Stirton and McGrew, 1935; Wilmarth, 1938).

Burge sand member of Valentine formation, Clarendonian, Cherry County, Nebraska (Johnson, 1936, p. 271-272).

[1]**Buttonwillow** local fauna, Blancan, Kern County, California; *Mimomys* mandible from well, 3174 feet below surface (Stirton, 1936a).

Cache Peak local fauna in Kinnick formation, Barstovian, Kern County, California (Simpson, 1933).

California Institute of Technology Locality 150, *see* Locality 150.

Calvert formation, (?)Hemingfordian, Chesapeake region, especially Calvert County, Maryland. On the basis of Cetacea and plants, the Calvert is correlated with the Tortonian; fragmentary land mammals suggest approximate correlation with the Sheep Creek local fauna, *i.e.*, the "lower Sheep Creek," or, possibly, a slightly earlier age (Berry, 1938; Clark *et al.*, 1904; Mansfield, 1936; Wilmarth, 1938).

Canyon Largo group, Tiffanian, (?)Clarkforkian, and Wasatchian of the San Juan Basin, northwestern New Mexico and a narrow fringe of southwestern Colorado; term resurrected to replace "San Juan Wasatch" (Holmes, 1877; Wilmarth, 1938).

Carpinteria formation, late Pleistocene, Santa Barbara County, California (Wilson, 1933; Wilmarth, 1938).

Castle Rock conglomerate, Chadronian, Douglas County, south of Denver, Colorado (Simpson, 1933; Wilmarth, 1938).

Catahoula formation, Whitneyan and/or somewhat older, Texas coastal plain (Wood and Wood, 1937, p. 129-136, 144; Wilmarth, 1938).

Cathedral Bluffs tongue of Wasatch, early Bridgerian, chiefly Sweetwater County, Wyoming and Moffat County, Colorado (Nace, 1936; 1939, p. 16-17, 26-30; Wilmarth, 1938).

Cedar Creek facies of Lower Brule, Orellan; type locality, Weld and Logan counties, Colorado, apparently higher in volcanic ash than typical Orella of Nebraska-South Dakota area. If considered a valid and appropriate member name, it would have priority over Orella (Simpson, 1933; Wilmarth, 1938).

[1]**Cedar Mountain** beds, western Nye County, Nevada, Clarendonian. *See* Esmeralda formation (Simpson, 1933; Stirton, 1936a; 1939c; Wilmarth, 1938).

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[1] Indicates omission from the correlation chart.

Cedar Run local fauna at base of Oakville sandstone, late Arikareean, Washington County, Texas coastal plain. Wood and Wood (1937, p. 130, 153, 137-140) used Cedar Creek, which, being incorrect by local usage and preoccupied, is here replaced by the correct local name, "Cedar Run."

Chadron formation, Chadronian, Nebraska, South Dakota, Wyoming, Colorado and North Dakota. Also called *Titanotherium* beds, lower White River, etc. (Clark, 1937; Simpson, 1933; Wilmarth, 1938).

Chadronian age, new provincial term proposed in this report.

Chalk Cliffs local fauna, Barstovian (or possibly Hemingfordian), occurs on the east side of the Yellowstone River, 22.5 to 23.2 and 28.3 miles north of the highway bridge over the Yellowstone River, at Gardiner, Park County, Montana. Although this fauna is known to numerous geologists and paleontologists and has long been collected by local amateurs, it has almost escaped mention in print. Perhaps comparable in age to the Deep River, it contains: *Merychippus cf. isonesus, Mylagaulus, "?Cosoryx,"* Proboscidea. The localities are shown as Tertiary on Douglass' map (Douglass, 1902, p. 241; *see also* Frick, 1937, p. 269, 319, 346, 411).

Chanac fanglomerate, a Clarendonian formation, Kern County, California (Simpson, 1933; Stirton, 1936a; Wilmarth, 1938).

[1]**Charleston** phosphate pits, South Carolina, source of numerous Pleistocene mammals (Hay, 1923, p. 361-368) and some older redeposited fossils (Stirton, 1936a, p. 176-177, Ashley River).

[1]**Ciego Montero** local fauna, late Pleistocene, in mud at bottom of Chapapote Hot Spring, Baños de Ciego Montero, 30 miles northwest of Cienfuegos, Cuba (Anthony, 1925-1926; Brown, 1913; Matthew, 1919; 1931).

[1]**Cita Canyon** local fauna, late Blancan, Randall County, Texas Panhandle (Johnston, 1938).

Clarendon local fauna, later Clarendonian, Donley County, Texas Panhandle, perhaps definable as a member of Ogallala, but not yet adequately defined as such (Simpson, 1933; Stirton, 1936a; Wilmarth, 1938).

Clarendonian age, new provincial term proposed in this report.

Clark Fork member of Polecat Bench formation, Park County, Wyoming, Clarkforkian, also used as faunal zone (Jepsen, 1940; Nace, 1936, p. 106-115; Simpson, 1933; 1937b).

Clarkforkian age, new provincial term proposed in this report.

[1]**Coalinga,** *see* North Coalinga.

Cold Spring local fauna in the Oakville-Lagarto, definitely later than Garvin Gully, either Hemingfordian or early Barstovian, Texas coastal plain (Frick, 1937, p. 605-606; Plummer, 1932, p. 727-739; Wilmarth, 1938).

[1]**Collins Draw** local fauna in the Ogallala, Clarendonian or Hemphillian, Wallace County, Kansas (Hesse, 1936, p. 68-69; Stirton, 1936a).

Columbia local fauna (preoccupied as a geographic term, *cf.* Wilmarth, 1938) in "auriferous gravels," Clarendonian, Tuolumne County, California (Stirton, 1936a).

Conard local (fissure or "cave") fauna, Pleistocene, Newton County, Arkansas (Brown, 1908).

[1]**Continental Peak** formation, tentatively considered Uintan, Fremont and Sweetwater counties, Wyoming (Nace, 1939, especially p. 21-25).

Cook Ranch formation, Orellan, Beaverhead County, Montana (Simpson, 1933; Wilmarth, 1938).

[1]**Cooper Creek** local fauna, Wasatchian, Albany County, Wyoming (Nace, 1936, p. 54-55).

Coso Mountains local fauna, Coso formation, Blancan, Inyo County, California (Schultz, 1937; Stirton, 1936a).

Crazy Mountain field, geographic term including exposures of Bear, Lebo and Melville formations, *q.v.*, chiefly in Sweetgrass County, Montana.

Crocker Springs local fauna, later Barstovian, Kern County, California (Barbat and Weymouth, 1931; Stirton, 1936a).

Cumberland local (cave) fauna, Pleistocene, Allegany County, Maryland (Gidley and Gazin, 1938).

Curtis Ranch local fauna in the San Pedro Valley formation, early Pleistocene, Cochise County, Arizona (Simpson, 1933; Stirton, 1936a).

[1]**Cuyama** local fauna, Barstovian or Clarendonian, a very unfortunate term, since it does not occur in the Cuyama formation of the same area, with which it is inevitably confused. Gazin will replace Cuyama fauna with Quatal Canyon, *q.v.*

Cypress Hills formation, Chadronian, southern Saskatchewan. Within the Chadronian, its exact age is not altogether clear and may not be the same, throughout; the microfauna, as a whole, seems later than Pipestone Springs (McLearn, 1928; Russell, 1934; Simpson, 1933; Wilmarth, 1938).

Dad local fauna, Wasatchian, western Carbon County, Wyoming. Wasatchian mammals have been found east of the Washakie Basin, in the general neighborhood of Dad P.O., just under the Tipton tongue of the Green River.

DeBeque formation, late Paleocene and Wasatchian of western Colorado, to be named and described by Patterson; the Plateau Valley local fauna occurs near its base (Simpson, 1933, as "Ruby").

Deep River formation, early Barstovian, Meagher County, Montana. Strictly speaking, this term is preoccupied by the abandoned Deep River of Emmons, but no possible confusion can result from its continued use for the Tertiary formation, a usage which is recognized by the U. S. Geological Survey. Deep Creek, Smith Creek and Smith River beds are synonyms (Simpson, 1933; Wilmarth, 1938).

[1]**Devil's Gulch** beds, Ogallala, Brown County, Nebraska. Although this term has been less used, it precedes "Valentine," *q.v.*, and was adequately defined, stratigraphically, from the first, in terms of what was then known. If redefined, it is available to replace "Valentine formation," if the latter be considered preoccupied or unduly ambiguous (Barbour, 1914a; 1914b; Simpson, 1933; Stirton, 1936a; Wilmarth, 1938).

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[1] Indicates omission from the correlation chart.

Douglas Flat local fauna in "auriferous gravels," Whitneyan, Calaveras County, California (Leidy, 1869, p. 388, 390).

Dragon local fauna in North Horn "formation," Dragonian, Emery County, Utah (Gazin, 1938; 1939).

Dragonian age, new provincial term proposed in this report.

Duchesne River formation (=Duchesne, preoccupied), Duchesnean, Duchesne and Uinta counties, Utah (Kay, 1934; Simpson, 1933; Wilmarth, 1938).

Duchesnean age, new provincial term proposed in this report. There is no general agreement that the Duchesnean should be considered latest Eocene rather than earliest Oligocene.

[1]**Eden beds,** *see* Mount Eden (Simpson, 1933; Stirton, 1936a; Wilmarth, 1938).

Edmonton formation, upper Cretaceous, Alberta (Wilmarth, 1938).

Edson local fauna in Ogallala, Hemphillian, Sherman County, Kansas (Hibbard, 1939a; Simpson, 1933; Stirton, 1936a; Wilmarth, 1938).

Ellensburg formation, Clarendonian, Kittitas County, Washington (Simpson, 1933; Stirton, 1936a; Wilmarth, 1938).

Eocene epoch (Osborn, 1929, p. 64-101, Pls. IV-XII; Simpson, 1933; Smith, 1900; Wilmarth, 1925, p. 52-54).

Esmeralda formation, Clarendonian, Esmeralda and Nye counties, Nevada, equivalent to, and antedates, Fish Lake Valley, *q.v.* (Simpson, 1933; Stirton, 1936a; 1939c; Wilmarth, 1938).

Etchegoin formation, Hemphillian, Kern County, California (Simpson, 1933; Stirton, 1936a; Wilmarth, 1938).

Evanston formation, tentatively called early Paleocene, Uinta County, Utah (Nace, 1936, p. 42-46; Wilmarth, 1938).

Feldt Ranch local fauna in Ogallala at type locality, Hemphillian, Keith County, Nebraska (Stirton, 1936a).

Fish House clay, Pleistocene, Camden County, New Jersey (Hay, 1923, p. 301-303; Wilmarth, 1938).

Fish Lake Valley local fauna in Esmeralda formation, *q.v.*, Clarendonian, Esmeralda County, Nevada. "VanderHoof has traced the beds at Fish Lake Valley through to the type section of the Esmeralda [and] the fauna is the same."—Stirton and VanderHoof, letter dated November 29, 1939. (Simpson, 1933; Stirton, 1939c).

Flagstaff limestone, a formation presumably of late Paleocene age, Wasatch Plateau, central Utah (Wilmarth, 1938).

Flaxville gravel, a formation of Clarendonian or possibly Barstovian age, or perhaps both, northern Montana (Simpson, 1933; Wilmarth, 1938).

Flint Creek local fauna and "beds," an inadequately described formation, early Barstovian, probably about equivalent to Deep River formation, Granite County, Montana (Simpson, 1933; Wilmarth, 1938).

Florissant formation, Oligocene, perhaps Orellan, Teller County, central Colorado. In spite of the remarkable collections from the Florissant lake beds, the paleontologic evidence as to age is both uncertain and conflicting, and there is no strat-

igraphic evidence. The only mammal, *Peratherium*, is known from the Oligocene and John Day, and is most abundant in the Cedar Creek facies (largely Orellan). The paleobotanical evidence has usually been interpreted in favor of much more recent age, but R. W. Chaney writes (letter dated December 9, 1939): "The Florissant flora is as closely related to the Green River flora as to the Lower John Day (Bridge Creek) flora. . . . Possibly it is the same age as the [Chadronian] Castle Rock formation of Colorado." The compromise determination as Oligocene and perhaps Orellan represents a return to the opinions of Cope, Lesquereux, and Scudder (Gazin, 1935; Wilmarth, 1938).

Fort Logan formation, inadequately described as a lithologic unit, Arikareean, Meagher County, Montana (Simpson, 1933; Wilmarth, 1938).

[1]**Fort Niobrara,** a loose, obsolete term for the Ogallala near Valentine, Nebraska (Simpson, 1933; Stirton, 1936a, p. 195; Wilmarth, 1938).

Fort Union series or group, often called a formation, Paleocene, type locality, Buford, North Dakota, also South Dakota, Montana, and Wyoming (Jepsen, 1940; Nace, 1936, p. 66-87; Simpson, 1933; 1937a, especially p. 20-28; Wilmarth, 1938).

Fossil Lake local fauna (also proposed as a formation), latest Pleistocene, Lake County, Oregon (Elftman, 1931; Hay, 1927, p. 241-245; Wilmarth, 1938).

Fowkes formation of Wasatch group, tentatively called late Paleocene, southwestern Wyoming (Nace, 1936, p. 149-151; Simpson, 1933, p. 114; Wilmarth, 1938).

[1]**Frankstown Cave** local fauna, Pleistocene, Blair County, Pennsylvania (Peterson, 1926).

Fullers Earth Company local fauna, here proposed (with G. G. Simpson's approval) for the Hawthorn B local fauna found half a mile south of Midway (referred to as [1]Midway by Simpson and also sometimes called [1]Quincy), Hemingfordian, Gadsden County, western Florida (Simpson, 1932, especially p. 11-16).

Garvin Gully local fauna near the base of the Oakville sandstone, earliest Hemingfordian (or possibly, late Arikareean), including the greater part of Hay's composite [1]Navasota "fauna," *q.v.* (Hay, 1924a).

Gering formation of Arikaree group (or member of Arikaree formation) early Arikareean, western Nebraska, especially Scotts Bluff, Morrill, Sioux and Dawes counties (Lugn, 1939b, especially p. 1251-1252, Pl. I; Simpson, 1933; Wilmarth, 1938).

Goliad sand, a Clarendonian, Hemphillian, and (?)Blancan formation, Texas coastal plain (Wilmarth, 1938). Chief mammal locality on Buckner Ranch, Bee County, overlain by fossiliferous Pleistocene, with artifacts (Sellards, 1939, 1940a).

[1]**Goodnight** local fauna in Ogallala, Hemphillian, Armstrong County, Texas Panhandle (Simpson, 1933; Stirton, 1936a; Wilmarth, 1938).

Gracias formation (=[1]Tapasuma, Stirton, 1936a), Clarendonian, Honduras (Olson and McGrew, 1938).

[1]**Grand View** local fauna (name preoccupied by formation in same region, *see* Wilmarth, 1938), late Blancan, Owyhee County, Idaho (Stirton, 1936a).

Gray Bull member of "Bighorn Wasatch", *q.v.*, early Wasatchian, Park, Bighorn and Washakie counties, Wyoming. Although usually considered a faunal zone, it

[1] Indicates omission from the correlation chart.

should be considered a member of the so-called "Bighorn Wasatch", a formation for which no valid name has yet been proposed; *see* Wasatch. It essentially preoccupies the Greybull sandstone (Hewett, 1926; Nace, 1936, p. 115-120; Simpson, 1933; Wilmarth, 1938).

Green Cove formation, Bridgerian, Fremont County, Wyoming (Wilmarth, 1938).

Green River formation, late Wasatchian to Bridgerian, Wyoming, Utah and Colorado (Bradley, 1931; Burke, 1935; Nace, 1936, p. 176-192, 208; 1939, p. 26-31; Wilmarth, 1938).

[1]**Guymon** local fauna, Texas County, Oklahoma, Hemphillian, *see* Optima (Frick, 1937, p. 8, 144-145, 500-506, 514, 517-518).

Hagerman formation, Hagerman lake beds, late Blancan, Twin Falls and Gooding counties, Idaho (Gazin, 1936, p. 281-290; Stearns, Crandall, and Steward, 1938, p. 52-56; Simpson, 1933; Stirton, 1936a; Wilmarth, 1938).

Halfway member of Duchesne River formation, Duchesnean, Uinta County, Utah; described as a horizon (Wilmarth, 1938).

[1]**Hanna** formation, supposedly Paleocene and Wasatchian, Carbon County, Wyoming and adjoining areas. Fragmentary fossil mammals are known (Nace, 1936, p. 51-55).

[1]**Harper** local fauna (preoccupied as geographic term, *see* Wilmarth, 1938), Hemphillian, Malheur County, Oregon (Stirton, 1936a).

Harrison formation of Arikaree group, late Arikareean, chiefly in Sioux County, Nebraska. Name technically preoccupied by Harrison diorite of Merrill. (*Cf.* Wilmarth, 1938; *see*, however, Ashley *et al.*, 1933, p. 434, Article 7 (f) permitting retention of both names.) A conceivable alternative would be to redefine and substitute Rosebud, which is available and more or less equivalent (Cook and Cook, 1933, p. 28-37; Lugn, 1939b; Schultz, 1938; Simpson, 1933; Wilmarth, 1938).

Hawthorn formation, Hemingfordian, Florida, also Georgia and South Carolina. Land mammal localities are confined to northern Florida (Simpson, 1933; Wilmarth, 1938).

Hay Springs local fauna, mid-Pleistocene, Sheridan County, Nebraska (Barbour and Schultz, 1937).

Hell Creek formation, latest Cretaceous, chiefly Montana (Nace, 1936, p. 37-38; Wilmarth, 1938).

Hemingford group, composed of Marsland and Sheep Creek formations, Hemingfordian, northwestern Nebraska (Lugn, 1938, p. 226-227, Pl. I).

Hemingfordian age, new provincial term proposed in this report.

Hemphill (or [1]Coffee Ranch, or [1]Miami) local fauna occurs well up in Hemphill member, Hemphillian, Hemphill County, Texas Panhandle (Simpson, 1933; Stirton, 1936a).

Hemphill member, proposed as "beds" and "formation," but apparently a member of the Ogallala, Hemphillian, chiefly Hemphill County, Texas Panhandle (Reed and Longnecker, 1932; Simpson, 1933; Stirton, 1936a; Wilmarth, 1938).

Hemphillian age, new provincial term proposed in this report.

Hiawatha member of Wasatch group, Wasatchian of Sweetwater County, Wyoming and Moffat County, Colorado (Nace, 1936, p. 156; 1939; Nightingale, 1930; Wilmarth, 1938).

Higgins local fauna in Hemphill member of Ogallala, early Hemphillian, Lipscomb County, Texas Panhandle. Stirton (1936a) and Hesse (1940) place it below the Hemphill local fauna on paleontologic grounds.

[1]**High Rock Canyon,** [1]Little High Rock Canyon, southern outliers of the Virgin Valley formation, *q.v.* (Merriam, 1910, p. 51, 209-210, Pl. I; Stirton, 1939c).

Horsetail Creek facies of Chadron formation, Chadronian, Weld and Logan counties, Colorado (Simpson, 1933; Wilmarth, 1938).

Huerfano formation, Wasatchian and early Bridgerian, Huerfano County, Colorado; fragmentary fossils occur in the "unfossiliferous" lower beds (Simpson, 1933; Wilmarth, 1938).

Hunter Canyon formation, late Montanan to early Lance, western Colorado (Wilmarth, 1938).

[1]**Idaho** formation, usually considered late Pliocene and Pleistocene, Idaho and Oregon (Merriam, 1918b; Simpson, 1933; Wilmarth, 1938).

Indian Meadows formation, Wasatchian, northwestern Fremont County, Wyoming (Denison, 1937; Love, 1939, p. 58-63).

Ironside local fauna and beds, Clarendonian, Malheur County, Oregon (Simpson, 1933; Stirton, 1936a; Wilmarth, 1938).

Irvington local fauna, Pleistocene, Alameda County, California (Stirton, 1939a, p. 394-402).

Jacalitos formation, Kern County, California; the Hemphillian Jacalitos local fauna (*Neohipparion molle* zone) probably differs in age from the typical Jacalitos (Stirton, 1936a).

John Day equivalent south of Three Forks, Gallatin County, Montana, Arikareean (Wood, 1933; 1938).

John Day formation, early Arikareean and (?)Whitneyan, chiefly Wheeler and Grant counties, Oregon. In spite of the extensive fauna of the John Day, its correlation is by no means certain. It shows some affinities with the fauna of the upper Brule (Whitney member), but more with the Monroe Creek, Rosebud, and other Arikareean faunas. In general, John Day mammals which are comparable to Great Plains forms fall into two groups: the first is close to, or identical with, Arikareean forms; the second seems more progressive than Whitneyan, but less progressive than Arikareean forms. This might be interpreted either as correlating with the earlier Arikareean (the interpretation adopted in this report), or as occupying a considerable time interval between the Brule and Arikaree (for the existence of which there is no other evidence). The lower John Day, nearly devoid of fossil mammals, is very tentatively considered Whitneyan (Collier, 1914, p. 3-21, map; Hodge, 1932; Jillson, 1928; Merriam, Stock, and Moody, 1925, p. 45-49; Simpson, 1933; Wilmarth, 1938).

Junior Oil Company Beard No. 1 Well, formation unknown, Torrejonian, Caddo Parish, northwestern Louisiana (Simpson, 1932b; Jepsen, 1940, p. 243).

[1] Indicates omission from the correlation chart.

Kern River formation, Hemphillian, Kern County, California (Stirton, 1936a; Wilmarth, 1938; Wilson, 1937).

Kew Quarry local fauna in Sespe formation or group, Whitneyan or possibly later, Ventura County, California; the quarry is situated approximately at the Tsp 50° dip sign, Las Posas Hills (Kew, 1924, Pl. I; *see also* Stock, 1932; 1933).

Kimball formation of Ogallala group, presumably Hemphillian or Blancan, mammalian fauna not yet described, southwestern Nebraska, northeastern Colorado, and western Kansas (Lugn, 1939b, p. 1258-1264, Pl. I).

Kinnick formation, Hemingfordian and Barstovian, Kern County, California (Wilmarth, 1938), called informally, [1]Monolith or [1]Monolith series (Simpson, 1933).

Kirkwood formation, Miocene, New Jersey coastal plain; the Squankum local fauna seems Arikareean and the Shiloh marl may well be late Hemingfordian (Kümmel, 1911, p. 14-20; Lewis and Kümmel, 1915, p. 71-72; Mansfield, 1936; Wilmarth, 1938).

Knight formation of the Wasatch group (type Wasatch), Wasatchian (fauna equivalent to that of the Lysite), Uinta County, Wyoming (Nace, 1936, p. 151-155; Simpson, 1933; Wilmarth, 1938).

La Barge local fauna, presumably in Knight formation, late Wasatchian, north of Tulsa (now La Barge), Sublette County, Wyoming (Bonillas, 1936). This occurrence demonstrates a Lost Cabin fauna within the general area which has always been included in the type "Wasatch," occurring only 24 miles in a direct line from outcrops of the Knight formation as mapped by Veatch (1907, Pl. III). Fossils also occur in sections 28 and 29, T. 28 N., R. 112 W.

Lacualtipan (or [1]Zacualtipan) local fauna, Hemphillian, Hidalgo, Mexico (Freudenberg, 1922; Stirton, 1936a).

Lagarto clay, about late Barstovian to early Clarendonian, a Texas coastal plain formation (Wilmarth, 1938).

Lake Lahontan beds, late Pleistocene formation of northwestern Nevada (Merriam, 1918a; Wilmarth, 1938).

Lance formation, latest Cretaceous, Wyoming, Montana, South Dakota, and North Dakota. The flora is not "of Fort Union aspect" (Dorf, 1939; Lull, 1915; Nace, 1936, p. 30-36; Simpson, 1927; Wilmarth, 1938).

Lapoint member(?) of Duchesne River formation, described as horizon, Duchesnean, Uinta County, Utah (Wilmarth, 1938).

Largo local fauna and faunal zone, Wasatchian, hardly definable as a member (and certainly not yet so defined) of the Canyon Largo group, Rio Arriba County, New Mexico (Simpson, 1933; Wilmarth, 1938).

Laverne local fauna in Ogallala, late Clarendonian, Beaver County, Oklahoma Panhandle (Hesse, 1936, as Lavern; Stirton, 1936a, as [1]Beaver; Wilmarth, 1938).

[1]Lawler Ranch local fauna in Petaluma formation, Hemphillian or Blancan, Sonoma County, California (Stirton, 1936a; 1939a, p. 389-393).

Lebo formation or member of Fort Union, chiefly Torrejonian, Montana (Nace, 1936, p. 87-91; Simpson, 1933; 1937a, p. 20-56; Wilmarth, 1938).

Leuciscus turneri lake beds, an unnamed formation underlying the Madison Valley formation, on the east side of the lower Madison River, south of Logan, Gallatin County, Montana, presumably Hemingfordian, Barstovian, or both. Without evidence and incorrectly it was called "White River" by Douglass (1903, p. 199 and Plate II; *see also* Wood, 1938).

Lissie formation, early Pleistocene, Texas coastal plain (Plummer, 1932, p. 781-787; Wilmarth, 1938).

Little White River formation(?) and local fauna, Clarendonian, Todd County, South Dakota (Simpson, 1933; Stirton, 1936a; Wilmarth, 1938).

Locality 150 of Sespe, Duchesnean, Ventura County, California, about 3 miles NNW. of the town of Simi (Kew, 1924, Pl. I; *see also* Stock (1932a), and numerous other papers).

Long Island local fauna, Hemphillian, Phillips County, Kansas (Stirton, 1936a). This name is technically preoccupied as a geographic term and likely to mislead. (*Cf.* Wilmarth, 1938.)

Lost Cabin equivalent in the "Bighorn Wasatch," Bighorn Basin, Wyoming; at Tatman Mountain (Granger, 1914, p. 202, 207); east of Yellowstone Park (Jepsen, 1939); *see also* [1]McCullock Peak.

[1]**Lost Cabin** equivalent of Sublette County, Wyoming, *see* La Barge.

Lost Cabin member (or formation) of Wind River formation (or group), Wasatchian, Fremont, and Natrona counties, Wyoming, proposed as a formation by Sinclair and Granger (1911, p. 104). Although considered a faunal zone by Wilmarth (1938), following Osborn (1929), it is, unquestionably, a valid, mapable lithologic unit (Simpson, 1933; Wood, Seton, and Hares, 1936).

[1]**Loup Fork** or [1]Loup River, obsolete or obsolescent terms of vague significance for continental late Cenozoic of western North America. Deposits covering almost all of the Miocene and Pliocene have been called Loup Fork at various times, and, even in the most restricted sense in which it was generally used, the Loup Fork would cover approximately the Barstovian, Clarendonian, and Hemphillian of the present report. It seems not to have been employed recently (except as a historical synonym, *e.g.*, Scott, 1937, p. 109) by any qualified authority. Loup River, technically speaking, is of Pleistocene age (Simpson, 1933; Wilmarth, 1938).

Lower Brule=Orella member, Orellan.

[1]**Lower Harrison** member or formation, Arikareean; *see* Harrison; it contains the Agate Quarries (Simpson, 1933, p. 99).

Lower mammal zone of the Green River, late Wasatchian, Uinta County, Utah (Burke, 1935).

Lower Ravenscrag, latest Cretaceous formation of southern Saskatchewan (Fraser *et al.*, 1935).

Lower White River=Chadron formation, *q.v.*

Lysite equivalent in the "Bighorn Wasatch," Bighorn Basin, Wyoming, Wasatchian (Granger, 1914, p. 202, 207).

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[1] Indicates omission from the correlation chart.

Lysite member (or formation) of Wind River formation (or group), Wasatchian, Fremont County, Wyoming; *see* references under Lost Cabin, also Berry (1932).

Madison Valley formation, Barstovian, Gallatin County, Montana. The upper, unconsolidated beds may, in future, be distinguished as a Clarendonian unit (Simpson, 1933; Teilhard and Stirton, 1934, p. 281; Wilmarth, 1938).

Manix lake beds, a Pleistocene formation, San Bernardino County, California (Hay, 1927, p. 160-161; Merriam, 1915; Wilmarth, 1938).

Manti facies of Green River formation, also (?)Wasatchian local fauna. It was probably deposited in a separate lake which, however, belonged to the Green River lake drainage system (Wilmarth, 1938).

Mantua lentil at the bottom of the Polecat Bench formation, Puercan, Park County, Wyoming (Jepsen, in Scott, 1937, p. 99, 230; Jepsen, 1940).

Marsland formation (="Upper Harrison"), early Hemingfordian, northwestern Nebraska; the fauna is still largely undescribed (Cook and Cook, 1933, p. 28-37; Lugn, 1939b, p. 1253-1254, Pl. I).

Martin Canyon "beds." Whitneyan and Arikareean, Logan County, Colorado; a poorly defined formation? or group? or referable to the standard formations to the northeast? (Simpson, 1933; Wilmarth, 1938).

Mascall formation, early Barstovian, chiefly Grant County, Oregon (Collier, 1914, p. 3-21, map; Jillson, 1928; Merriam, Stock, and Moody, 1925, p. 49-58; Simpson, 1933; Wilmarth, 1938).

McCarty's Mountain, so far as available knowledge goes, is merely a locality term for Oligocene exposures on its slopes or at its base, in northwestern Madison County, Montana. Douglass divided the exposures into several successive fossiliferous levels, but his unpublished notes have not yet been located; much or all of the Oligocene may be represented (Douglass, 1905, p. 209-211).

[1]**McCullock Peak** local fauna, Wasatchian, Park County, Wyoming (Hewett, 1920, p. 547-550). The case for early Bridgerian, as opposed to Lost Cabin age, rests entirely on the identification of a third upper molar, U. S. Nat. Mus. No. 15847, as *Helaletes*. Re-examination leaves it as indeterminate between *Helaletes* and the most *Helaletes*-like species of *Heptodon*. Hence the McCullock Peak local fauna is best interpreted as of Lost Cabin age.

McKittrick brea, late Pleistocene, Kern County, California, in view of its peculiar character, is perhaps best considered as a Pleistocene formation of very restricted area, instead of merely a local fauna (Schultz, 1938).

Medio Creek local fauna in Goliad formation, Hemphillian, Bee County, Texas (Plummer, 1932, p. 760).

Melbourne bone bed, late Pleistocene formation, various localities, especially on the east coast, particularly Brevard and Indian River counties, Florida (Cooke and Mossom, 1929, p. 198, 218-226; Wilmarth, 1938).

Melville formation, or member of Fort Union, Tiffanian, Sweetgrass County, Montana (Simpson, 1937a, p. 21-25).

[1]**Metamynodon** sandstone facies, channel sandstones scattered in lower part of Orella member of Brule, South Dakota, Nebraska and Wyoming (Wanless, 1922).

Middle White River=lower Brule=Orella member, Orellan.

Minnechaduza local fauna, late Clarendonian, or, possibly, early Hemphillian, replacing [1]Valentine local fauna, Ogallala, Cherry County, Nebraska (Stirton, 1939b).

Mint Canyon formation, Clarendonian and (?)Barstovian, Los Angeles County, California (Eaton, 1939; Jahns, 1939; Simpson, 1933; Stirton, 1936a; Wilmarth, 1938).

Miocene epoch (Osborn, 1918; Simpson, 1933; Stirton, 1939c; Teilhard and Stirton, 1934; Wilmarth, 1925, p. 52-53).

[1]**Mohave** or Mojave beds, *see* Barstow (Simpson, 1933; Wilmarth, 1938).

Monroe Creek formation of Arikaree group, Arikareean, Sioux County, Nebraska and adjoining area (Lugn, 1939b; Simpson, 1933; Wilmarth, 1938).

Mount Eden formation, Hemphillian, Riverside County, California (Simpson, 1933; Stirton, 1936a; Wilmarth, 1938).

[1]**Muddy Creek** formation, Muddy Valley beds, Clarendonian?, Lincoln County, Nevada (Simpson, 1933; Wilmarth, 1938).

Mulholland local fauna in Orinda(?) formation, Hemphillian, Contra Costa County, California (Stirton, 1939a, p. 366-388).

Myton member of Uinta formation (=Uinta C, "true Uinta," *Diplacodon* zone), late Uintan, Uinta and Duchesne counties, Utah (Kay, 1934; Nace, 1936, p. 232-241; Wilmarth, 1938).

[1]**Nacimiento** group, includes Puerco and Torrejon formations, San Juan Basin, northwestern New Mexico (Simpson, 1933; Wilmarth, 1938).

[1]**Navasota,** a vague, misleading term. "Navasota beds" is an obsolete term for the Oakville and Lagarto of the coastal plain in the general neighborhood of Navasota, Texas. Hay's "Navasota fauna" is now known to be composite; the largest component is the Garvin Gully, *q.v.*, or "[1]Navasota Quarry" which is low in the Oakville; the [1]Noble farm (now [1]Barry farm) local fauna occurs considerably higher in the less consolidated portion of the Oakville, half a mile south of Wood's, and may prove to be roughly equivalent to the Cold Spring local fauna, *q.v.*; VanderHoof and Gregory (1940, p. 159) consider it Barstovian or, possibly, Clarendonian. To these elements, Hay added *Aelurodon francisi* from a well at a third locality, from an undetermined, and perhaps undeterminable, level (Hay, 1924a; Teilhard and Stirton, 1934, p. 282, 284; Wilmarth, 1938; Wood and Wood, 1937, p. 140).

Niobrara River local fauna, late Barstovian, Ogallala, Cherry County, Nebraska, also called [1]Railroad Quarry local fauna (Johnson, 1936; McGrew and Meade, 1938; Simpson, 1933; Stirton, 1939b; Stirton and McGrew, 1935; Wilmarth, 1938).

North Coalinga (or Coalinga) local fauna in top of Temblor formation, early Barstovian, Fresno County, California (Bode, 1935; Simpson, 1933).

North Horn, proposed as a formation by Spieker in an unpublished manuscript and referred to by Gazin (*see* references under Dragon), Cretaceous and Paleocene, central Utah. The "North Horn" almost certainly will require further subdivision.

[1] Indicates omission from the correlation chart.

[1]**Nussbaum** formation, Ogallala outlier? of south central Colorado (Wilmarth, 1938).

[1]**Oak Creek** local fauna in Little White River formation, Clarendonian, Todd County, South Dakota; name apparently preoccupied as a geographic term (Simpson, 1933; Stirton, 1936a; Wilmarth, 1938).

Oakdale local fauna, Hemphillian, Stanislaus County, California (Stirton, 1936a). Name apparently preoccupied as a geographic term. (*Cf.* Wilmarth, 1938.)

Oakville sandstone, a Miocene formation, Texas coastal plain (Plummer, 1932, p. 727-739; Simpson, 1933; Wilmarth, 1938; Wood and Wood, 1937, p. 133, 137-140, 144).

Ogallala group (often called a formation), Pliocene and latest Miocene of Nebraska, Kansas, Colorado, the Oklahoma Panhandle, northwest Texas, eastern New Mexico, and southeastern Wyoming. Perhaps the Little White River and similar patches in South Dakota should be included as outliers; the possible reference of more distant outliers is still uncertain. (Hesse, 1935; 1936, especially map on p. 69; Lugn, 1938, p. 220-227, 1939; Simpson, 1933; Stirton, 1936a, p. 184; Wilmarth, 1938).

Ojo Alamo formation or group, upper Cretaceous, northwestern New Mexico (Matthew, 1937, p. 345-348; Wilmarth, 1938).

Oligocene epoch (Osborn, 1918; 1929; Simpson, 1933; Wilmarth, 1925, p. 53-54).

Optima local fauna in Ogallala, Hemphillian, Texas County, Oklahoma (Hesse, 1936b; Stirton, 1936a).

Orella member of Brule formation, Orellan, Nebraska, South Dakota and Wyoming (Schultz and Stout, 1938).

Orellan age, new provincial term proposed in this report.

Oreodon beds=middle White River=lower Brule=Orella member, Orellan.

Orinda formation, Clarendonian, Contra Costa and Alameda counties, California (Simpson, 1933; Stirton, 1936a; 1939a; Wilmarth, 1938).

Paleocene epoch, recognized by virtually all North American mammalian paleontologists and recently adopted by the U. S. Geological Survey. The five-fold subdivision of the Paleocene, proposed in this report, runs counter to the implicit assumption that all geological time units, for some occult reason, are "naturally" divisible into thirds. For occasions when it is convenient to employ three subdivisions of Paleocene time, Puercan can be called "early," Dragonian and Torrejonian, "middle," and Tiffanian and Clarkforkian, "late" Paleocene (Jepsen, 1940; Matthew, 1937; Simpson, 1933; 1937a; Smith, 1900; Wilmarth, 1925, p. 54-56).

[1]**Palo Duro** beds=[1]Goodnight, *q.v.* (Simpson, 1933; Wilmarth, 1938).

Panaca formation and local fauna, Hemphillian?, Lincoln County, Nevada (Simpson, 1933; Stirton, 1936a; Wilmarth, 1938).

[1]**Panhandle** formation, proposed by Gidley for the pre-Clarendon beds of the Texas Panhandle, but usually treated as the Texas equivalent of the Ogallala, and not in regular current use in either sense (Simpson, 1933). If an unambiguous term, in the latter sense is desired, [1]Llano Estacado formation is available (*see* Wilmarth, 1938).

Paskapoo formation, possibly a group or series, late Paleocene, perhaps including earlier elements, Alberta (Russell, 1929; Simpson, 1933; Wilmarth, 1938).

Pawnee Creek beds, early Barstovian, Weld and Logan counties, Colorado, presumably a formation, but poorly defined: its stratigraphic relations to the Ogallala, above ("[1]Upper Pawnee Creek" or Sand Canyon), requires clarification, also its relation to the upper part of the Sheep Creek formation (Simpson, 1933; Wilmarth, 1938).

[1]**Payette** formation, Miocene of Idaho and Oregon; *see* Sucker Creek (Wilmarth, 1938).

[1]**Petaluma** formation, late Hemphillian or early Blancan, Sonoma County, California (Stirton, 1939a, p. 389-393; Wilmarth, 1938).

Phillips Ranch local fauna in Kinnick formation, Hemingfordian, Kern County, California (Simpson, 1933).

[1]**Pine Creek** local fauna in Ogallala, Clarendonian?, Sheridan County, Nebraska (Stirton, 1936a); name preoccupied as geographic term (*see* Wilmarth, 1938).

Pinole tuff, a Hemphillian formation, Contra Costa County, California (Simpson, 1933; Stirton, 1936a; 1939a; Wilmarth, 1938).

Pipestone Springs (also Pipestone, preoccupied, and Pipestone Creek), early Chadronian local fauna and inadequately described formation, composed of confluent alluvial fans filling valleys in crystallines, Jefferson County, Montana (Matthew, 1903; Simpson, 1933; Wilmarth, 1938).

"Pittsburgh" local fauna, Blancan, Contra Costa County, California, preoccupied as a geographic term (*cf.*, Wilmarth, 1938) and objectionable due to the natural mental association with Pittsburgh, Pa. It is understood that C. E. Weaver is replacing it by the Los Medanos formation (Stirton, 1936a; 1939a).

Plateau Valley beds, local fauna and (?) member at bottom of DeBeque formation (to be described by Patterson), Tiffanian, between Grand Junction and Rifle, western Colorado (Patterson, 1939; Wilmarth, 1938).

Pleistocene, commonly considered as an "epoch," which forms almost the entire [1]Quaternary "period," despite its exceedingly short duration—fairly certainly shorter than most, if not all, of the ages recognized in this report. *See* the various local faunas discussed: American Falls, [1]Anguilla, Bautista, Beaumont, [1]Bigbone Lick, Broadwater, Carpinteria, [1]Charleston, [1]Ciego Montero, Conard, Cumberland, Curtis Ranch, Fish House, Fossil Lake, [1]Frankstown, Hay Springs, Irvington, Lake Lahontan, Lissie, Manix, McKittrick brea, Melbourne, [1]Port Kennedy, Potter Creek, Rancho La Brea, Rodeo, Samwel, [1]Seminole field, Tequixquiac, [1]Trinidad, Tulare and Tule. Additional references: Anthony (1925-1926); Blackwelder (1939); Cooke and Mossom (1929, p. 233-279); Felix and Lenk (1890; 1891); Freudenberg (1910; 1921; 1922); Gut (1938a and b); Hay (1914; 1923; 1924b; 1927); Hibbard (1939b); Holmes and Simpson (1931); Matthew (1919; 1931); Miller (1916; 1922; 1929); Muellerried (1934); Olson (1940); Romer (1933); Sellards (1940, 1940b); Simpson (1928; 1929b; 1930); Sternberg (1930); Wilkerson (1932); Wilmarth (1925, p. 47-53).

Pliocene epoch (Stirton, 1936a; 1939c; Wilmarth, 1925, p. 51-53).

[1] Indicates omission from the correlation chart.

Polecat Bench formation, proposed by Jepsen (1940) for Paleocene ("Fort Union") of Park County, Wyoming.

[1]**Port Kennedy** local (cave) fauna, Pleistocene, Montgomery County, Pennsylvania (Hay, 1923, p. 311-320).

Potter Creek local (cave) fauna, late Pleistocene, Shasta County, California (Hay, 1927, p. 212-218).

Poway conglomerate, a formation of early Uintan age, San Diego County, California (Stock, 1937, 1938, 1939; Wilmarth, 1938).

Powder River Basin local faunas. Wasatchian, Johnson and Campbell counties, Wyoming. Between North and Middle Pumpkin Buttes, Campbell County, on the Pfister Ranch, in the first draw south of the Pfister Ranch buildings, *Coryphodon* occurs in beds of Gray Bull aspect, about 4 feet above the contact with beds of Paleocene aspect presumably the [1]Ulm formation of the Fort Union. Most of Middle Pumpkin Butte, above this saddle, is of Lysite aspect, but, so far, has proved unfossiliferous. Badlands of Wasatchian aspect occur about 2 miles south of Sussex, Johnson County, Wyoming, with sparse fragmentary fossils (*e.g.*, Alvin Locy ranch) suggesting a fauna of Gray Bull age (Jepsen, 1940, p. 242; Nace, 1936, p. 104-106; Wegemann, 1917; Wilmarth, 1938, under Ulm coal group).

Protoceras-Leptauchenia beds=upper White River=upper Brule=Whitney member of Brule, Whitneyan.

Puercan age, new provincial term proposed in this report. (*Cf.* Jepsen, 1940, p. 326.)

Puerco formation, Puercan, San Juan County, New Mexico (Dane, 1932; Matthew, 1937; Simpson, 1933; Wilmarth, 1938).

Quatal Canyon, Barstovian or Clarendonian local fauna, Ventura County, California. Gazin is replacing his "[1]Cuyama fauna" (1930), a preoccupied and misleading term, by Quatal Canyon. Gazin regarded these beds as equivalent to the Barstow, an opinion which he still holds (letter dated June 15, 1940). A. E. Wood (1937) considered them Clarendonian, an opinion concurred in by VanderHoof (1939) on other grounds. Wood's, *cf. Plesippus*(?) might well be *Hypohippus.*

Rancho La Brea local fauna, late Pleistocene, Hancock Park, Los Angeles, California. The Rancho La Brea brea might well be considered a formation of very limited extent and peculiar character (Merriam, 1911; Stock, 1929; 1930a).

Randlett (?)member of Duchesne River formation, described as a horizon, Duchesnean, Uinta County, Utah (Wilmarth, 1938).

Rattlesnake formation, Hemphillian, Grant and Wheeler counties, Oregon (Collier, 1914, p. 3-21, map; Merriam, Stock, and Moody, 1925; Simpson, 1933; Stirton, 1936a; Wilmarth, 1938).

Ravenscrag "formation," latest Cretaceous and supposed Paleocene of southern Saskatchewan (Fraser *et al.*, 1935; Wilmarth, 1938).

[1]**Red Rock Canyon,** preoccupied and abandoned,=Ricardo, *q.v.* (Simpson, 1933; Wilmarth, 1938).

[1]**Republican River** "formation," Pliocene and late Miocene of Kansas and southern Nebraska: in a broad sense, Republican River is simply the Ogallala of this area and is a superfluous synonym; in any narrower sense, it is artificial and com-

posite so that more restricted local (unit) faunas should be employed (Lugn, 1939b, p. 1271-1273; Simpson, 1933; Stirton, 1936a; Wilmarth, 1938).

Rexroad local fauna in Ogallala, late Blancan, Meade County, Kansas (Hibbard, 1937, p. 240; 1939c, also called [1]Rexford, by misprint).

Rhinoceros Hill local fauna in Ogallala, Hemphillian, Wallace County, Kansas (Stirton, 1936a) Wilmarth, 1938).

Ricardo formation, Clarendonian, San Bernardino County, California (Simpson, 1933; Stirton, 1936a; Wilmarth, 1938).

Rock Bench local fauna in Polecat Bench formation, Torrejonian, Park County, Wyoming (Jepsen, in Scott, 1937, p. 99, 230; Jepsen, 1940).

[1]**Rock Creek** beds, Pleistocene, Swisher County, Texas, preoccupied,=Tule formation, *q.v.* (Wilmarth, 1938).

Rodeo local fauna, Pleistocene, Contra Costa County, California (Stock, 1925, p. 201), name preoccupied as a geographic term (*see* Wilmarth, 1938).

Rome local fauna, Hemphillian, Malheur County, Oregon (Stirton, 1936a; Wilson, 1937, p. 3-13), preoccupied as a geographic term (*see* Wilmarth, 1938).

[1]**Rooks** (or [1]Plainville) local fauna, Hemphillian, Rooks County, Kansas (Stirton, 1936a).

[1]**Rosamond** group, *see* Barstow (Simpson, 1933; Wilmarth, 1938).

Rosebud beds, Arikareean, southern South Dakota. It is still not certain whether the Rosebud is equivalent to the Harrison (in which case it might be substituted if the Harrison is considered technically preoccupied), or more probably, to the Monroe Creek and Harrison, together, or is a distinct facies of the Harrison, or, possibly, a distinct facies, member, or formation of the Arikaree group (Lugn, 1939b; Simpson, 1933; Wilmarth, 1938).

Sage Creek formation, early Uintan, Beaverhead County, Montana (Simpson, 1933; Wilmarth, 1938).

Samwell local (cave) fauna, late Pleistocene, Shasta County, California (Hay, 1927, p. 213-216).

Sand Canyon local fauna (to replace misleading "[1]Upper Pawnee Creek"), presumably in the Ogallala, Clarendonian, Weld County, Colorado. Simpson (1933, p. 105) considers it nonexistent, Stirton (1936a) calls it "Upper Pawnee Creek"; reinvestigation is indicated.

Sand Coulee, early Wasatchian local fauna and (?)faunal level, Park County, Wyoming. At present, it is not clearly separable as a member of either Gray Bull or "Bighorn Wasatch" (Simpson, 1933; Wilmarth, 1938).

Sand Wash local fauna, Uintan, in an outlier of the Washakie (presumably B), occupying an isolated basin in Moffat County, Colorado, largely in T. 9 and 10 N., R. 97, 98 and 99 W. (Abel and Cook, 1925; Cook, 1926a and b; Sears, 1924, p. 295, Pl. XXXV; Sears and Bradley, 1924, Pl. XXIV; Simpson, 1933, p. 91).

San Joaquin clay, a Blancan formation, Kern County, California (Stirton, 1936a; Wilmarth, 1938).

[1] Indicates omission from the correlation chart.

San Pedro Valley formation (=San Pedro of Simpson, 1933, preoccupied), late Blancan and early Pleistocene, Cochise County, Arizona (Simpson, 1933, Stirton, 1936a).

San Timoteo local fauna and (?)formation, Blancan, Riverside County, California (Simpson, 1933; Stirton, 1936a).

Santa Fe formation, predominantly Barstovian and Clarendonian, Rio Grande Basin, north central New Mexico. Frick (1937, p. 8, "Upper Rio Grande" local fauna) apparently implies that his parties have found a Hemphillian element in the Santa Fe; in any case, C. E. Needham, director of the New Mexico Bureau of Mines, states (letter dated December 19, 1939) that Gazin identified a *Plesippus* tooth and a *Rhyncotherium* jaw from the Santa Fe formation, near Socorro, indicating the presence of a still later (Blancan) element (Bryan and McCann, 1937-1938; Cabot, 1938; Denny, 1940a and b; Henderson, 1913; Hunt, 1934; Simpson, 1933; Smith, 1938; Stirton, 1936a; Wilmarth, 1938).

[1]**Seminole field** local fauna, Pleistocene, Pinellas County, Florida. Seminole is preoccupied as a geographic term (*Cf.* Wilmarth, 1938; *see also* Holmes and Simpson, 1931; Simpson, 1929a).

Sespe formation (or group?), Uintan to Arikareean, inclusive, Ventura County, California (Simpson, 1933; Stock, numerous papers, including 1932a and b; 1938b; Wilmarth, 1938).

Shark River marl, a formation of early Bridgerian age, Monmouth County, New Jersey. A tillothere tooth from "near Shark River," *Anchippodus riparius* Leidy (1868), now in the Philadelphia Academy of Sciences, seems to be indistinguishable from *Tillotherium*, so far as known, and hence, indicates Bridgerian age for the deposit from which it was derived (almost certainly the Shark River marl). This indication, outweighing the suggestion of Wasatchian age from the presence of *Barornis regens* Marsh (which resembles *Diatryma*), agrees with the invertebrate evidence (Leidy, 1869, p. 403, Pl. XXX, figs. 45, 46; Wilmarth, 1938).

Sharktooth Hill local fauna in top of Temblor formation, Barstovian, Kern County, California (Hanna, 1930; Wetmore, 1930).

Sheep Creek formation, mainly Hemingfordian, northwestern Nebraska (Cook and Cook, 1933, p. 38-44; Lugn, 1939b; Simpson, 1933; Wilmarth, 1938); *see also* Box Butte.

Sheep Creek local fauna (="Lower Sheep Creek," Cook and Cook, 1933, p. 38-40).

Shiloh marl, upper member or facies of the Kirkwood formation, Cumberland and Salem counties, New Jersey, rather probably late Hemingfordian. Since the Shiloh marl is correlated with the Calvert on the basis of invertebrates (Mansfield, 1936, p. 169), and the Calvert, *q.v.*, tentatively, with the Sheep Creek, the Shiloh marl may also be correlated with the latter, still more tentatively. The type and unique specimen of *Tapiravus validus* Marsh is the only mammal known from the Shiloh marl (Kümmel, 1911, p. 14, 20; Wilmarth, 1938).

Siesta formation (=Orinda-Siesta of Stirton, in part), Clarendonian, Contra Costa County, California (Simpson, 1933; Stirton, 1936a; 1939a; Wilmarth, 1938).

Silver Coulee local fauna and "beds," Polecat Bench formation, Tiffanian, Park County, Wyoming (Jepsen, in Scott, 1937, p. 99, 230; Jepsen, 1940).

Skull Spring local fauna, early Barstovian, Malheur County, Oregon (Simpson, 1933).

[1]**Smiths Valley** local fauna, Hemphillian, Lyon County, Nevada (Wilson, 1936).

South Mountain local fauna in Sespe formation, Arikareean, Ventura County, California (Kew, 1924, Pl. I; Stock, 1930b), preoccupied as a geographic term. (*Cf.* Wilmarth, 1938.)

Snake Creek beds, facies, member, or formation of Ogallala, Sioux County, Nebraska. It is still uncertain how many temporally distinguishable faunas occur; nor can the Snake Creek faunas safely be used in detailed correlation, due to the frequent vagueness or unreliability of the field records regarding these complicated channel deposits (Cook and Cook, 1933, p. 41-58; Simpson, 1933; Stirton, 1936a; Wilmarth, 1938).

Squankum local fauna, at the base of the Kirkwood, *q.v.*, about late Arikareean, south of Farmingdale, Monmouth County, New Jersey (Marsh, 1893, p. 409-412, Pls. IX, X; Wood, 1939).

Stewart Spring local fauna, Barstovian, said to be redeposited in the [1]Cedar Mountain beds (Esmeralda), western Nye County, Nevada (Simpson, 1933, p. 92; Stirton, 1932, p. 61; 1936a, p. 183; 1939c).

Sucker Creek local fauna, apparently in the Payette formation, early Barstovian, Malheur County, Oregon (Scharf, 1935).

[1]**Sweetgrass,** [1]Sweetgrass County,=Crazy Mountain field, term largely abandoned (Simpson, 1933).

Swift Current Creek formation (name to be so emended by Russell, from [1]Swift Current formation, preoccupied), late Uintan, southern Saskatchewan (Simpson, 1933; Wilmarth, 1938).

Tapo Ranch local fauna in Sespe formation, *q.v.*, late Uintan about 3 miles north-northwest of the town of Simi (Kew, 1924, Pl. I), Ventura County, California.

[1]**Tatman Mountain** gravels, age post-Wasatchian but otherwise uncertain (Wilmarth, 1938).

Tecuya member and local fauna (red beds at base of "Monterey"), early Arikareean, Ventura County, California; also called Tecuja (Simpson, 1933; Stock, 1932c; Wilmarth, 1938).

Tehama formation, Blancan, Tehama County, California (Simpson, 1933; Stirton, 1936a; Wilmarth, 1938).

Tehuichila local fauna, Hemphillian, Vera Cruz, Mexico (Freudenberg, 1922; Stirton, 1936a).

Temblor formation, mainly Hemingfordian, contains the early Barstovian North Coalinga local fauna near its top, Kern County, California (Simpson, 1933, as North Coalinga; Wilmarth, 1938).

Tequixquiac local fauna, early Pleistocene, Valley of Mexico (Furlong, 1925, p. 138-139, 144-152).

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[1] Indicates omission from the correlation chart.

Tepee Trail formation, Uintan, northwest Fremont County, Wyoming (Love, 1939, p. 73-79).

Thomas Farm local fauna,=Hawthorn A, early Hemingfordian, Gilchrist County, Florida (Simpson, 1933; Teilhard and Stirton, 1934; White, 1940).

Thompson Creek local fauna and clay containing it, early Chadronian, southern Broadwater County, Montana. The fauna (chiefly a microfauna) appears to be exactly equivalent to that of the Pipestone Springs formation; whether the beds can properly be assigned to the Pipestone Springs formation is still uncertain (Douglass, 1902, p. 242).

Thousand Creek formation, Hemphillian, Humboldt County, Nevada (Simpson, 1933; Stirton, 1936a; 1939c; Wilmarth, 1938).

Tick Canyon formation, early Hemingfordian, unconformably underlying the Mint Canyon, Los Angeles County, California (Jahns, 1939).

Tiffanian age, new provincial term proposed in this report.

Tiffany local fauna in the lower part of the Canyon Largo group, specifically at the "Mason pocket," often used in a more extended sense as a faunal level, Tiffanian, La Plata County, Colorado. The Tiffany almost certainly could and should be redefined as either a member or a formation, but additional field work is desirable before this is done (Simpson, 1933; 1935; Wilmarth, 1938).

Tipton tongue of the Green River formation, late Wasatchian, chiefly Moffat County, Colorado, and Sweetwater County, Wyoming (Nace, 1936, p. 192-194; 1939; Wilmarth, 1938).

Titanotherium beds=Chadron formation, or, sometimes, approximately,=Chadronian of this report.

Titus Canyon formation, early Chadronian, Death Valley, California (Stock, 1936; Stock and Bode, 1935; Wilmarth, 1938).

Toluca locality of *Teleoceras fossiger* jaw, (?)Clarendonian, Mexico (Cope, 1884).

Tongue River member of Fort Union, Montana, North Dakota, and Wyoming, Torrejonian (Nace, 1936, p. 91-94; Simpson, 1933; Wilmarth, 1938).

"Tonopah" local fauna in (?)Esmeralda formation, Barstovian, Nye County, Nevada (Furlong, 1935; Stock, 1934), preoccupied as a geographic name (*cf.* Wilmarth, 1938), to be described by Henshaw.

Torrejon formation, Torrejonian, San Juan and Sandoval counties, New Mexico; type locality progressively limited by Gardner (1910, p. 713) and by Sinclair and Granger (1914, p. 310); *see also* Matthew (1937), Simpson (1933), Wilmarth (1938).

Torrejonian age, new provincial term proposed in this report. (*Cf.* Jepsen, 1940, p. 326.)

Toston beds, scanty local fauna and(?) formation, Orellan, Broadwater County, Montana (Wilmarth, 1938).

[1]**Trinidad** local faunas (name preoccupied as formal term, *cf.* Wilmarth, 1938), Pleistocene and Hemingfordian of Trinidad, West Indies (Schaub, 1935).

[1]**Truckee** formation, Miocene, Nevada and California (Simpson, 1933; Wilmarth, 1938).

Tulare formation, about early Pleistocene of the west side of the San Joaquin Valley, California (Simpson, 1933; Wilmarth, 1938).

Tule formation, early Pleistocene, Rock Creek, Briscoe County, Texas Panhandle (Wilmarth, 1938).

Tullock formation, early Paleocene, Montana (Dorf, 1940, p. 223-231; Nace, 1936, p. 38-40; Wilmarth, 1938).

[1]**Turtle-Oreodon** layer, the richly fossiliferous zone near the base of the Orella member of the Brule, South Dakota, Nebraska, and Wyoming (Sinclair, 1921).

Twin Buttes member of Bridger formation (=Bridger C+D), later Bridgerian, southwestern Wyoming (Wilmarth, 1938).

Uinta equivalent at Beaver Divide and Badwater, Fremont and Natrona counties, Wyoming; either an unnamed Uintan formation or *cf.* Tepee Trail (Nace, 1936, p. 235-237; Wood, Seton, and Hares, 1936).

Uinta formation, Uintan, Duchesne and Uinta counties, northeastern Utah. Although the Uinta is one of the better known mammal-bearing formations, several curious misconceptions about it are entrenched in the literature. Thus the lower Uinta (Wagonhound member, A+B) is referred to the Bridger formation by the U. S. Geological Survey and others. This result is apparently obtained by calling the Washakie "Bridger," a questionable procedure, and then, because the upper Washakie and lower Uinta are approximately equivalent, calling the lower Uinta, "Bridger," also. This is then, frequently, followed by mental telescoping, so that the lower Uinta is correlated with the upper fossiliferous Bridger (C+D) of the Bridger Basin. Again, it is often suggested that the lower Uinta should be correlated with Bridger E. However, it seems curious to correlate the fossiliferous lower Uinta with the essentially unfossiliferous Bridger E; if they are correlated (a speculative procedure at best), the reverse correlation would seem greatly preferable, that is, to correlate the less defined Bridger E with the fossiliferous Wagonhound member of the Uinta. And, if the Washakie must be correlated out of existence, it would seem far preferable to call the lower Washakie (A), upper Bridger, and the upper Washakie (B), lower Uinta, since both Bridger and Uinta are far more fossiliferous than the Washakie. Again, Uinta A is repeatedly stated to be entirely unfossiliferous but to be correlated [on what grounds?] with the upper Bridger (Twin Buttes member, C+D), in whole or in part. Even if the "*Metarhinus* zone" be included in Uinta B, some fossils are known from Uinta A, representing a Uinta faunule (including *Amynodon* and *Protoreodon*, which are unknown in the Bridger or Washakie A, and *Hyrachyus grandis*, a more advanced species than any known from the Bridger). Thus it seems strongly probable that Uinta A is later than Bridger D but that the time interval between them is short. The exact relation of Bridger E to this hypothetical interval and to the earlier Uinta must remain entirely speculative until recognizable fossil mammals are found (Kay, 1934; Nace, 1936, p. 232-242; Simpson, 1933; Wilmarth, 1938; Wood, 1934, p. 241-257).

Uintan age, new provincial term proposed in this report (not to be confused with the Cambrian "Uintan series" of C. R. Keyes, *see* Wilmarth, 1938).

Upper Brule=Whitney member, Whitneyan.

[1] Indicates omission from the correlation chart.

[1]**Upper Harrison,** early Hemingfordian, *see* Marsland formation (Simpson, 1933, p. 99).

Upper mammal zone of the Green River formation, early Bridgerian, Uinta County, Utah (Burke, 1935).

[1]**Upper Pawnee Creek,** *see* Sand Canyon (Stirton, 1936a, p. 190).

Upper Ravenscrag=Fort Union? (Fraser *et al.*, 1935).

Upper White River=upper Brule=Whitney member, Whitneyan.

Valentine formation (of Nebraska Geological Survey and others) of Ogalalla group, Nebraska, especially Cherry County, Barstovian and Clarendonian (Johnson, 1936; 1938; Lugn, 1938; 1939a and b; Simpson, 1933). Although the Valentine formation is usually considered to date from 1917, it was not adequately defined at that time nor until long afterwards (1933 or 1936, according to one's standard of adequacy). It is therefore legitimate to argue that the Valentine of Barbour and Cook is preoccupied as a stratigraphic term by both the Valentine of Field, 1919, and of Hewett, 1931 (*see* Wilmarth, 1938). On the other hand, the term Valentine became well established in the literature as an informal time designation for the earlier phases of the continental Pliocene of North America, particularly because of its use in this sense by Matthew and others, in this country and abroad. Lately, due to more detailed work in northern Nebraska, the term Valentine has been applied in various ways by different authors, with the result that there has been serious confusion as to the meaning of the term. Stirton and McGrew (1935) showed that the Valentine beds as previously accepted have a considerable vertical range and limited the name to the upper local fauna in this sequence (Minnechaduza), thereby assigning it a position near the boundary between the lower and middle Pliocene. Johnson (1936) on the other hand, maintained that the name should be restricted to the lowest level of the sequence, which would make it of Upper Miocene affinities, in terms of the correlations tentatively adopted in this report. The arrangement on the accompanying correlation chart, essentially as proposed by the Nebraska Geological Survey, shows the term Valentine in a moderately inclusive sense as a formation, to embrace the two older local faunas, respectively of uppermost Miocene and lower Pliocene age (Niobrara River and Burge), but not the Minnechaduza. This usage more nearly accords with the manner in which the term had become established in the literature than either of the sharply restricted usages cited above. If Valentine is considered as preoccupied by Field's term, or by Hewett's, or by both, the name Devil's Gulch, *q.v.*, which was adequately described and defined by Barbour in 1914, is available for redefinition in this sense, *i.e.*, to replace the Valentine formation of the Nebraska Geological Survey.

[1]**Valentine** local fauna (of Stirton and others), replaced by Minnechaduza (Stirton, 1939b, p. 433), late Clarendonian or early Hemphillian, Cherry County, Nebraska (McGrew and Meade, 1938; Stirton, 1936a; Stirton and McGrew, 1935).

Virgin Valley formation, Humboldt County, Nevada, late Hemingfordian or early Barstovian (Simpson, 1933; Stirton, 1939c; Wilmarth, 1938).

Wagonhound member of Uinta formation (includes Uinta A and B, with their respective faunas), early Uintan, Uinta County, Utah (Wilmarth, 1938).

Wasatch, properly a group, usually called a formation, in southwestern Wyoming, especially Uinta County, early Eocene and (?)Paleocene. By unjustified extensions,

this term has come to include a wide variety of continental deposits of variegated colors in western North America, of uncertain age, presumed to be early Tertiary, as well as numerous actually dated deposits of Wasatchian age. In spite of its wide use in the literature, it is an unfortunate term, as the standard "Wasatch" faunas (those of the Bighorn and San Juan basins) occur in formations which are merely called "Wasatch," and the Wasatch group proper is almost without fossil vertebrates. In the Wasatch proper, the La Barge local fauna is equivalent to that of the Lost Cabin, and the Knight fauna to that of the Lysite. Thus the fossiliferous Wasatch is exactly equivalent, faunally, to the fossiliferous Wind River, which, according to most textbooks and standard manuals, is supposed to overlie it. The exceedingly tentative determinations of the Fowkes as late Paleocene, the Almy as mid-Paleocene, and the underlying Evanston as early Paleocene, do not rest on any satisfactory evidence. When the "Wasatch fauna" is spoken of, it means in practice one of two things: (1) lower Eocene, or Wasatchian of this report; or (2) Gray Bull. The latter usage is difficult to justify, as no fauna of Gray Bull age has yet been found in the type Wasatch, so that it is not certain that beds of that age are present. *See also* "Bighorn Wasatch," Canyon Largo, Cathedral Bluffs, [1]Cooper Creek, Dad, DeBeque, Hiawatha, Knight, La Barge, Lost Cabin, Powder River Basin, and Wind River (Nace, 1936, p. 120-146; Simpson, 1933; Wilmarth, 1938).

Wasatchian age, new provincial term proposed in this report. (*Cf.* Wasatchian series of Keyes.)

Washakie formation, late Bridgerian and early Uintan, Sweetwater County, Wyoming, *see also* Sand Wash and Uinta (Nace, 1936, p. 206-229; Simpson, 1933; Wilmarth, 1938).

[1]**Weller** local fauna, [1]Weller sandstone, [1]Weller horizon, Moffat County, Colorado,=lower Browns Park, *q.v.* (Simpson, 1933; Wilmarth, 1938).

White Butte local fauna, Whitneyan, southwestern North Dakota. It is proposed to limit White Butte, formally, to the "Upper White River" of this area, which differs strikingly from the Whitney member of the Brule, both faunally and lithologically. It seems to be a distinct facies, member, or even formation, but more field study is necessary to settle the question (Douglass, 1909, p. 228-237, 281-288; Leonard, 1922).

White Cone local fauna in Bidahochi formation, Hemphillian, northeastern Arizona (Stirton, 1936b; Wilmarth, 1938).

White River series or group, sometimes still considered a formation, Oligocene of western South Dakota and Nebraska, eastern Wyoming, northeastern Colorado, with small outliers in southwestern North Dakota and southeastern Montana; the Oligocene of western Montana should not be referred to the White River (O'Harra, 1920; Scott, Jepsen, and Wood, 1936-1940 and ?; Simpson, 1933; Wanless, 1922; 1923; Wilmarth, 1938).

Whitney member of Brule, Whitneyan, Nebraska and South Dakota (Schultz and Stout, 1938), apparently not preoccupied by the Whitney sand (Wilmarth, 1938, p. 2328), which appears to be a drillers' term, only.

Whitneyan age, new provincial term proposed in this report.

[1] Indicates omission from the correlation chart.

Wiggins formation, Chadronian?, northwestern Fremont County, Wyoming (Love, 1939, p. 79-85).

[1]**Willwood** formation, *see* "Bighorn Wasatch."

Wind River formation (or group?) mid- and late-Wasatchian, Fremont and Natrona counties, Wyoming (Baur, 1934; Love, 1939, p. 63-66; Nace, 1936, p. 160-175; Simpson, 1933; Wilmarth, 1938).

Wood Mountain gravels, Barstovian, Saskatchewan; despite the temptation to correlate this formation with the Flaxville gravel, the Canadian formation seems earlier (Simpson, 1933; Wilmarth, 1938).

Wray local fauna in Ogallala, Hemphillian, Yuma County, Colorado (Simpson, 1933; Stirton, 1936a).

W. R. Wilson Coal Mine, local fauna at Princeton, British Columbia, from which Bridgerian tillothere teeth were obtained (Russell, 1935).

Xmas and Kat quarries, local channel fauna or faunas in the Ash Hollow formation, later than the Minnechaduza, northeastern Cherry County, Nebraska (Frick, 1937, p. 8, 41-43, 268-269, 650-652).

Yoder formation (or member of Chadron?), early Oligocene, Goshen County, Wyoming. The known fauna is scanty, and that published is still scantier, but Schlaikjer's interpretation as later than Duchesne River and earlier than Chadron seems likely, although not demonstrated. It would be premature to attempt to settle the exact age relation of the Yoder to either the Titus Canyon or Pipestone Springs, but it may provisionally be considered as earliest Chadronian (Clark, 1937, p. 327-328; Wilmarth, 1938).

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This list is deliberately kept within reasonable limits and is not intended to be an exhaustive bibliography, although by the use of cross references it can be made to approximate one. The aim is rather to consult the convenience of the user than always to give credit to the original authority. References are made chiefly to: works with extensive, well-chosen bibliographies, such as Nace (1936), Simpson (1933), Stirton (1936a), and Wilmarth (1938); works of which the relevance has previously been overlooked; references to validate particular points; works of special importance, and, in general, relevant literature which has appeared within the last few years. Omission of a particular reference in a connection in which it would be expected usually means only that it can readily be located by cross-reference; this applies, particularly, to papers published before about 1933. Additional references may be found in: Hay's bibliographies of North American fossil vertebrates, Nickles' bibliographies of North American geology, and the Camp and VanderHoof bibliography of North American fossil vertebrates (Geol. Soc. Am., Spec. Papers, No. 27).

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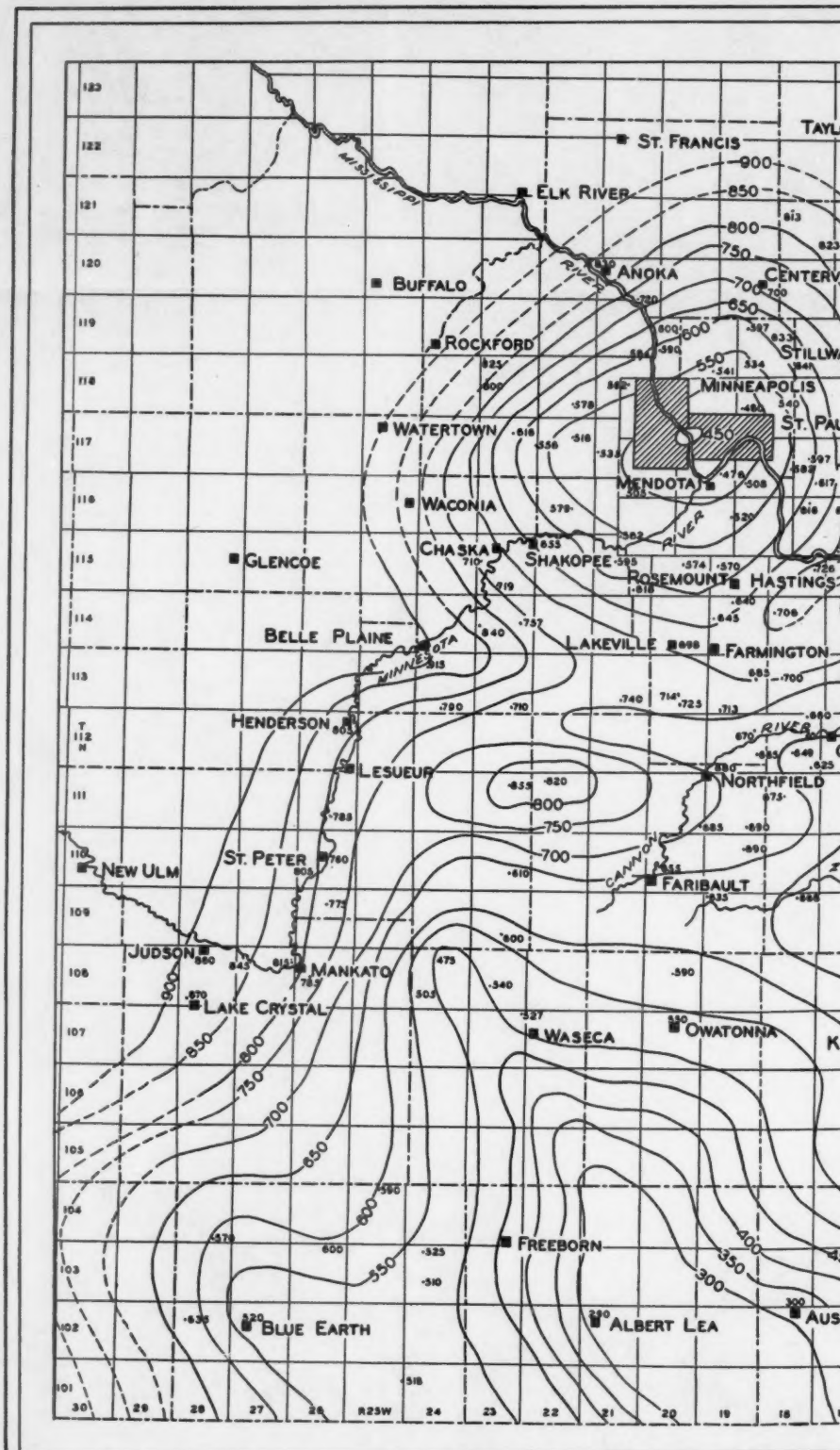

STRUCTURAL CONTOUR MAP

OUR MAP, SOUTHEASTERN MINNESOTA

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SUBSURFACE STRUCTURE OF THE PALEOZOIC ROCKS OF SOUTHEASTERN MINNESOTA

BY G. A. THIEL AND G. M. SCHWARTZ

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1. Structural contour map, southeastern Minnesota	49

ABSTRACT

Recent work by the Minnesota Geological Survey permits the construction of a detailed structural map of the southeastern part of the State with contours drawn on the Jordan-Oneota contact. The major structure is not the "Twin City" syncline as mapped formerly (Trowbridge, 1934) but a series of gently pitching troughs, basins, and domes.

In the region of the Twin Cities approximately 2500 square miles are underlain by a roughly circular basin around whose margin the Jordan-Oneota contact occurs at an elevation of 700 feet above sea level. The bottom of the basin, outlined by the 450-foot contour, is broad and flat. The average dip is about 20 feet per mile. The Hudson-Afton anticline modifies the structure of the east margin. Along the south edge of the basin an east-west-trending anticline extends directly across the area formerly mapped as synclinal. The area south of this structural high is characterized by a downward warping that formed a broad, gently pitching syncline whose major axis extends from southern LeSueur County southeastward into Iowa. There are

three minor dome-like structures and smaller folds on the east limb of the syncline. The elevation of the Jordan-Oneota contact rises from 200 feet above sea level in the region of Austin to over 1150 feet on the crest of a local high to the southwest of Winona. Faults occur along the valley of the St. Croix River north of Stillwater and along the Mississippi valley at Hastings and Red Wing.

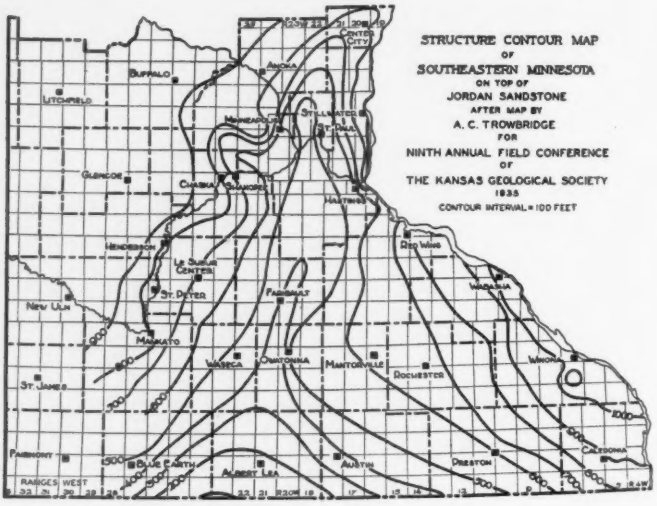

FIGURE 1.—*Structural contour map*
After map for Kansas Geological Society

INTRODUCTION

The major subsurface structure of southeastern Minnesota was recognized by N. H. Winchell and his associates. Their observations are recorded in the Annual Reports and in the Final Reports of the Geological and Natural History Survey of Minnesota, 1872 to 1900. They reported the two major structures of the region as (1) an artesian basin in the area of St. Paul and Minneapolis and (2) a broad synclinal trough in the southeastern counties. Winchell's (1884; 1888) maps of Goodhue, Dakota, and Rice counties indicate that the two structures referred to are separated by an anticlinal axis that extends from near Hastings in the valley of the Mississippi westward toward Belle Plaine, located in the valley of the Minnesota River.

More recently structural maps (Fig. 1) have been published (Trowbridge, 1934; 1935) (Bastin, 1939, Pl. 3) that erroneously connect the St. Paul-Minneapolis basin with the broad synclinal trough to the south. The two structures are shown as one trough that is called the "Twin City"

syncline. This supposed syncline extends from the Iowa-Minnesota State line, northward through Minneapolis and St. Paul, and then northeastward to connect with the axis of the Lake Superior basin (Van Hise and Leith, 1911, p. 622). These contour maps have been referred to by several students of stratigraphy and of tectonics, and consequently the structural errors are being perpetuated. The object of the present study is to submit data that will clarify these subsurface structural relations.

Previous difficulties were largely due to insufficient data. Intensive work by the Minnesota Geological Survey since 1932 now makes available much information based on outcrops and well logs. The differences between earlier structural maps and the present map may be seen by comparing Plate 1 and Figure 1.

STRATIGRAPHY

The rocks exposed at the surface in southeastern Minnesota are Cambrian, Ordovician, and Devonian. A few Cretaceous outliers occur in the southwestern part of the area. Pre-Cambrian rocks have been reached in a number of deep wells and are exposed at Taylors Falls, New Ulm, and in the region northwest of Elk River. Table 1 gives the sub-divisions according to the revised classification (Stauffer *et al.*, 1939).

The massive basal beds of the Oneota dolomite cap the bluffs along the major streams, and the Jordan-Oneota contact is exposed in the cliffs and steep slopes of many valley walls. Because of the numerous exposures of this contact and furthermore because of the uniform and readily identified lithology of both the Jordan and the Oneota formations, the top of the Jordan sandstone was chosen as datum for the construction of the structural map shown on Plate 1.

MAJOR SUBSURFACE STRUCTURES

Plate 1 shows that the major subsurface structures are essentially the same as those indicated by the early geologic maps of Winchell. The southern part of the area is characterized by a broad gently pitching syncline whose major axis extends from near LeSueur southeastward into Iowa. The Paleozoic and Keweenawan sediments included in this warped structure rest on an irregular granite surface that seems to slope much more steeply than the sedimentary strata. This relationship is indicated by the wedging of pre-Cambrian sandstones and shales against the granite slopes along both the east and the west margins of the basin. The great thickness of the Red Clastic series (Fig. 2) along the bottom of this pitching trough points to a large basin floored with granite when sedimentation began in Keweenawan time. Later the Paleozoic strata were deposited nearly horizontally over the Keweenawan sediments. Post-

TABLE 1.—*Rock formations of southeastern Minnesota*

Period	Subdivisions	Average thickness in feet
Pleistocene	Recent deposits	0– 100
	Wisconsin drift	0– 400
	Keewatin	
	Patrician	
	Iowan	
Cretaceous	Illinoian drift	?
	Kansan drift	?
	Nebraskan drift	?
	Dakota sandstone	0– 50
Devonian	Cedar Valley limestone	0– 150
Ordovician	Cincinnatian	
	Maquoketa shale	
	Mohawkian	
	Galena limestone	0– 250
	Decorah shale	50– 75
	Platteville limestone	10– 35
	Glenwood beds	5– 15
	St. Peter sandstone	75– 160
	Canadian	
	Shakopee dolomite	45– 100
	"New Richmond sandstone"	5– 40
	Oneota dolomite	80– 200
Cambrian	St. Croixian	
	Jordan sandstone	60– 100
	Van Oser member	
	Norwalk member	
	St. Lawrence formation	25– 70
	Lodi member	
	Nicollet Creek member	
	Franconia formation	100– 225
	Bad Axe member	
	Hudson member	
	Taylors Falls member	
	Ironton member	
	Dresbach formation	200– 500
	Galesville member	
	Eau Claire member	
	Mt. Simon member	
Keweenawan	Hinckley sandstone	50– 200
	Red Clastic series	0–2000
Pre-Cambrian granite		Unknown

Paleozoic warping has tilted the formations so that the top of the Jordan sandstone is 1050 feet above sea level along the Mississippi Valley south of Wabasha and less than 300 feet above sea level in the region between Albert Lea and Austin, an average dip of approximately 10 feet per mile.

The western limb is steeper, averaging about 12 to 15 feet per mile. It pitches southward approximately 400 feet in a distance of 75 miles.

The broad pitching syncline that dominates the southern part of the area is separated from the symmetrical Twin City basin by a structural

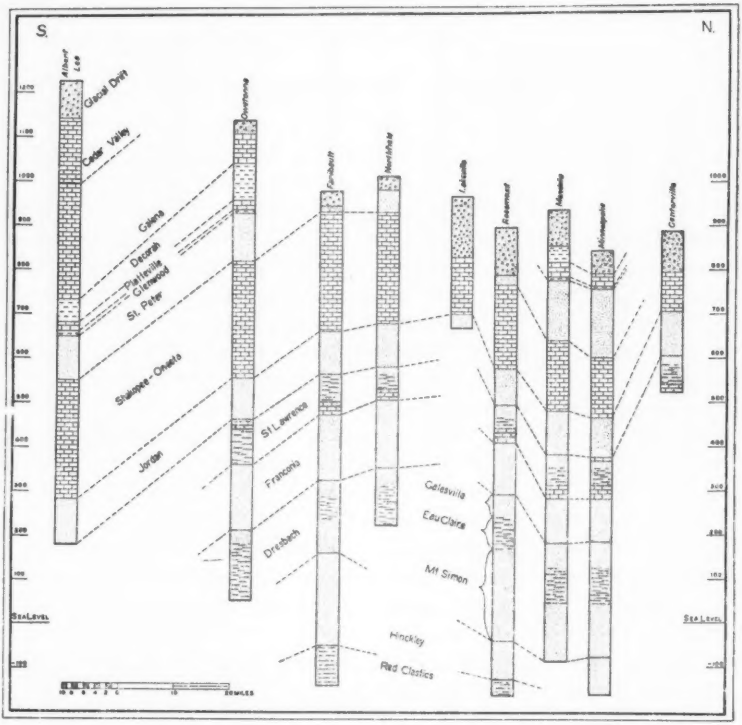

FIGURE 2.—*North-south geologic sections across southeastern Minnesota*

high, whose crest is highest in the region of Belle Plaine (Couser, 1935) where the top of the Jordan is more than 900 feet above sea level. From there it pitches gently eastward and levels out with the datum horizon at an elevation of approximately 700 feet. At this elevation it forms the saddlelike ridge that is the south rim of the Twin City basin. The ridge is conspicuous south of Farmington where it can be followed east to west for 25 miles. (*See* Winchell's county maps.) Hall (1905) states that the rocks are

"in the form of a great arch or dome, the crest of which seems to lie in Rice, Goodhue, and Dakota counties. From this dome the Trenton limestone is worn away and the St. Peter sandstone has been subjected to erosion almost sufficient to sever its southern from its northern area".

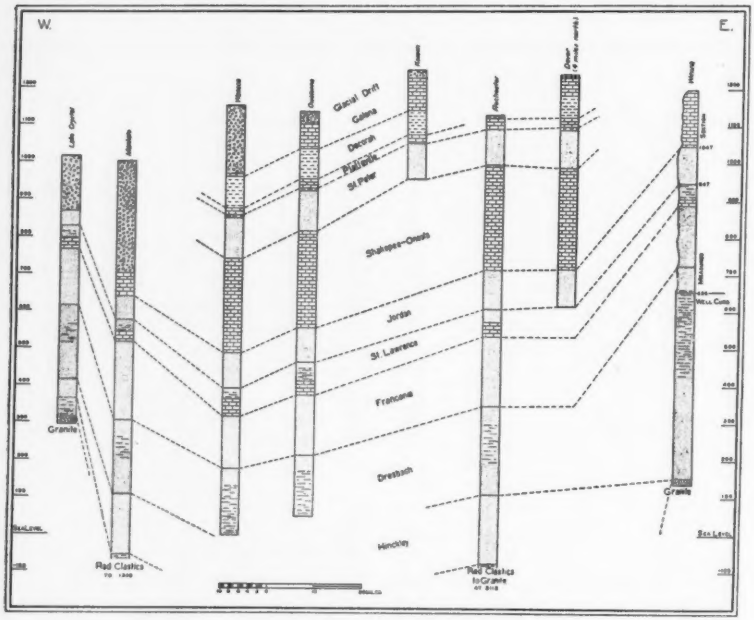

FIGURE 3.—*East-west geologic sections across southeastern Minnesota*

On Figure 1 this anticlinal axis is crossed by both the 600-foot and the 500-foot contours. The 400-foot contour extends northward beyond Faribault where, in reality, the top of the Jordan is as much as 650 feet above sea level (Fig. 2).

The northern part of the area under discussion is commonly referred to as the Twin City basin. The general structure of the rocks in the Minneapolis-St. Paul area is that of a shallow basin or saucer-shaped depression. The contour lines are based on outcrops and several hundred well logs. A few representative elevations of the Jordan-Oneota contact are shown on Plate 1. The basin is slightly elongate in a northeast-southwest direction with the lowest point about where the Minneapolis-St. Paul boundary line intersects the Mississippi River. The dip of the beds on the sides averages about 20 feet per mile though locally it departs

from this considerably. It is evident from the spacing of the structure contours that the bottom of the basin is nearly flat. This structure is an important artesian basin, for the Jordan sandstone and other sandy beds below are good aquifers. The detailed geology of the area has been described recently (Schwartz, 1936).

To some extent the Twin City basin coincides with a depression in the surface of the pre-Cambrian crystalline rocks.

MINOR SUBSURFACE STRUCTURES

AFTON ANTICLINE

Winchell (1888, p. 383) first recognized the existence of a definite anticlinal axis southwest of Afton. Later observers have explained the structure by a fault, but Trowbridge (1934, p. 521) returned to the anticlinal explanation. The main part of the structure, about 10 square miles in area, has now been mapped by plane table and telescopic alidade and elevations of outlying exposures have been determined by altimeter readings based on reliable bench marks. Figure 4 is a structural and geologic map based on this work (Schwartz, 1936, Fig. 36).

It is not possible to get information on contacts at the south end because only the Shakopee and Oneota dolomites are exposed, and the New Richmond horizon was not observed. At the northeast end a broad tributary valley of the St. Croix River is filled with drift and alluvial material. The anticline has a closure of more than 200 feet. At the south end it plunges sharply, and the Oneota is exposed along the creek in section 9, T. 27 N., R. 20 W. at 827 feet above sea level. Along the St. Croix River the Oneota is exposed at or near water level (elevation 675) from the mouth of Trout Creek to the junction of the St. Croix with the Mississippi at Point Douglas. Thus the Jordan-Oneota contact is somewhat below elevation 675. Clement's map (1935, Fig. 1) is obviously in error in placing the Jordan-Oneota contact between 700 and 750 along the St. Croix from Trout Creek nearly to the Mississippi, as the contact is actually below river level.

In the central part of the dome the Jordan and St. Lawrence formations and probably some Franconia are exposed. The lower formations are exposed mainly along Trout Creek and its tributaries. The Afton anticline is a local high, on the southwestward extension of the Hudson anticline (Trowbridge, 1934, p. 521), and the two structures may be referred to as the Hudson-Afton anticline.

MAZEPPA UPLIFT

Outcrops of the top of the Jordan sandstone along the Zumbro River and its tributaries in the region east of Mazeppa (Lundstrom, 1938) indi-

cate the presence of an elliptical uplift extending northwest to southeast for approximately 15 miles. The datum plane rises more than 200 feet above the general dip-slope of the regional structure that dominates that

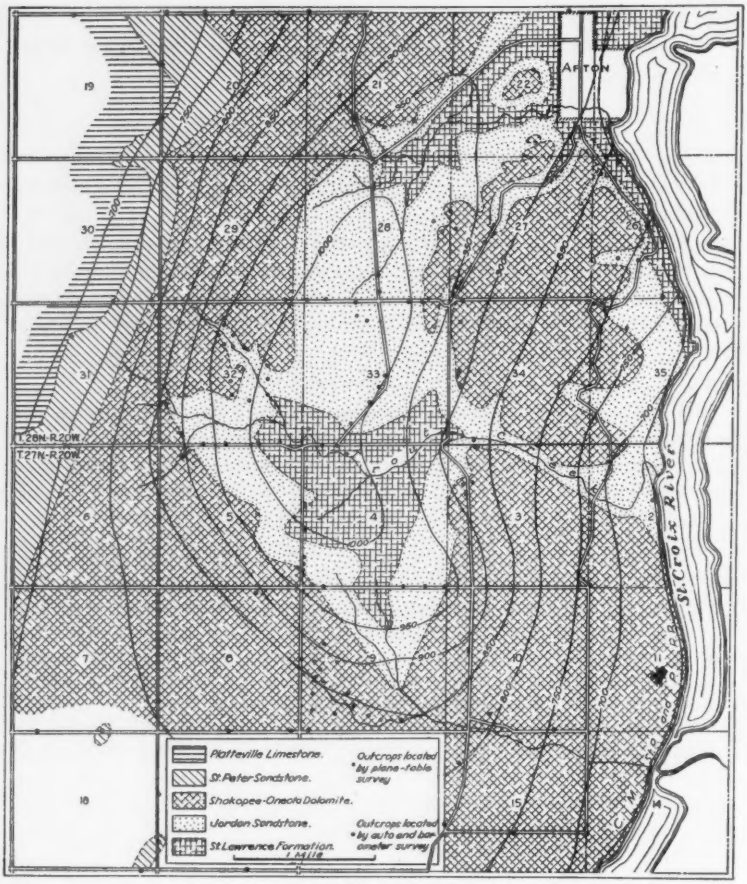

FIGURE 4.—*Geologic and structural contour map of Afton anticline*
(Courtesy, University of Minnesota Press.)

part of the state. A recent magnetometer survey of the uplifted area reveals a structural high also in the crystalline rocks of the basement complex.

SMALLER DOMES AND FOLDS

Other minor structures occur in the region southwest of Caledonia where a series of small folds trend in a general east-west direction. The structural contours of Plate 1 pass directly over these local irregularities. A local, small uplift south of Winona has lifted the top of the Jordan sandstone more than 100 feet above the general structure of the region. A similar local high occurs in the region between LeSueur and Northfield. Due to heavy morainic drift there are no outcrops in that region, and few wells reach bedrock. Consequently the details of the structure cannot be determined.

HASTINGS FAULTS

Good exposures of bedrock along the Mississippi and St. Croix rivers near their confluence indicate considerable disturbance. The Afton anticline pitches southward and seems to fade out about 5 miles north of Hastings.

On the east bluff of the Mississippi about a mile above Hastings, and within 1000 feet of the Hastings lock and dam, are two well-defined faults (Fig. 5). These faults were recognized by early geologists and are described by Winchell (1888, p. 384).

Above the dam the Jordan-Oneota contact is exposed 84 feet above normal pool level (elevation 687.2). The exposure is complete except for 5 feet above the water. On the north side of the larger fault the Oneota dolomite extends to and probably below water level. The larger fault strikes N. 70° E. and is downthrown on the northwest side about 100 feet. The smaller fault is about 300 feet upstream, its strike is estimated to be N. 45° E., and the downthrow, on the southeast, is perhaps 50 feet. A breccia shows fairly well near the top of the cliff along the plane of the larger fault. There are also poorly developed slickensides on the Oneota dolomite.

Another and probably larger fault lies in the channel of the Mississippi River opposite Hastings as was noted by Winchell (1888, p. 384) and by Trowbridge (1934, p. 524). Comparison of the data available at the outcrops already described with the elevation of the Jordan-Oneota contact in six wells in Hastings indicates a fault in the channel with a strike about N. 80° E. and a downthrow on the south side of 180 feet. A well recently drilled near the St. Croix River a mile above its mouth suggests that this fault extends eastward to the St. Croix.

RED WING FAULT

An abrupt difference in elevation of the top of the Jordan sandstone occurs in the City of Red Wing (Frey, 1937). At Memorial Park out-

crops of the Jordan-Oneota contact on the south side of a narrow eastward-trending valley are approximately 100 feet higher than the same horizon in Barn Bluff on the opposite side of the valley. On the northwestern side of Barn Bluff the base of the Jordan has an elevation of 745 feet,

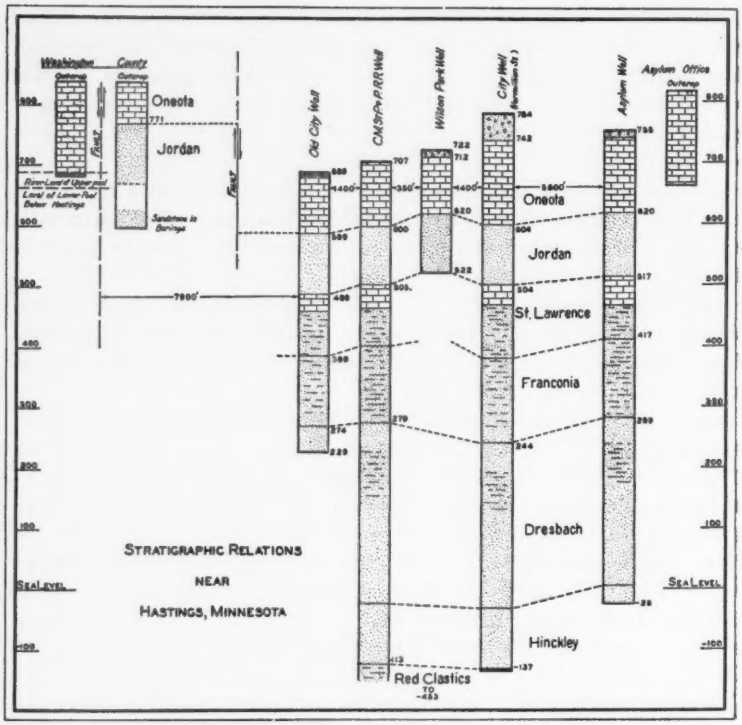

FIGURE 5.—*Geologic sections showing Hastings fault*

whereas at Memorial Park the same horizon is at 870 feet. The horizontal distance across the valley is less than a quarter of a mile. The downthrown side of the fault is to the north. The structure south of the fault conforms with the major regional dip toward the southwest. The throw of the fault seems to diminish westward, where it probably passes into a monoclinal fold, as indicated by the absence of the fault in the bluffs which should be intersected to the westward. Eastward the fault disappears beneath the recent sediments in the valley beyond Barn Bluff.

BLOCK FAULTED AREA

A small area of complex block faulting on the St. Croix River at the Soo Line drawbridge about 10 miles south of Taylors Falls has been described by Peterson (1927). The maximum displacement of 430 feet is represented by Decorah shale faulted downward against Franconia sandstone. At least three faults are known to exist in this small area, described in some detail by Peterson.

CONCLUSIONS

The Keweenawan and Paleozoic rocks of southeastern Minnesota have been deformed sufficiently to produce gently dipping domes, troughs, and basins. Since Cretaceous marine sediments overlap these structures unconformably, the folding was pre-Cretaceous. An earlier period of pre-Devonian warping is indicated also as the Devonian (Cedar Valley) limestone rests unconformably on Ordovician strata in the region of Albert Lea and Austin (Stauffer, 1922). The angularity is not great, but the structural relationship is more than a simple erosional disconformity. The major folding of the Upper Mississippi Valley is post-Pennsylvanian, pre-Cretaceous and thus it seems reasonable to assume that the major part of the deformation in southern Minnesota occurred at that time.

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University of Minnesota, Minneapolis, Minn.

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SOLUTION EFFECTS ON LIMESTONE AS A FUNCTION OF SLOPE

BY J. FRED SMITH, JR., AND CLAUDE C. ALBRITTON, JR.

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ABSTRACT

Jointed Cretaceous limestone forming dip slopes in the Sierra Blanca area, Texas, shows three fundamental types of solution effects: pits, facets, and furrows.

Solution pits of the shallow, subcircular, steep-walled variety called tinajitas form where rainwater is ponded in depressions on the limestones and are characteristic of surfaces inclined less than 3 degrees.

Solution facets, plane surfaces cut by corrosion, are found on the upper surfaces of joint blocks which pave slopes inclined from 3 to 6 degrees. Gentle initial slopes are necessary for the formation of facets, although the upper limit of slope at which facets may form has not been determined.

Solution furrows of the type that produce lapies form on slopes ranging from 20 to 90 degrees. Moderately steep slopes are necessary for the formation of furrows, and the lower limit of slope at which these features form lies between 6 and 20 degrees.

Corrosive effects in the Sierra Blanca area are primarily a function of the degree of slope on which meteoric water falls. Thus the principles of slope sculpture established for this area are applicable to other areas of similar bedrock and climate.

INTRODUCTION

In regions of slight rainfall most striking weathering effects on limestone are produced by solvent action. This curious fact, well known to students of arid regions (Blackwelder, 1927; Adkins, 1927, p. 18), impressed the writers while studying the dry country around Sierra Blanca, Texas (Fig. 1). Here, moreover, the solution features developed on limestone slopes proved to be essentially alike only on slopes of the same inclination, for degree of slope and type of solution feature are correlative.

This area is excellently suited to a study of this phenomenon. Within a radius of 10 miles from Sierra Blanca the relatively homogeneous Lower Cretaceous Finlay limestone forms flat caps or gentle slopes of cuestas or steep dip slopes of hogbacks.

The Finlay is typically dense, and beds rarely exceed 5 feet in thickness. It is evenly bedded. Small quantities of quartz silt and sand in scattered grains stand in relief on weathered surfaces. Calcareous shells are abundant in some layers but do not affect effectual homogeneity. Nearly everywhere strike and dip joints cut the bedding at high angles.

Finlay limestone forms dip slopes along a portion of Devil Ridge, a large hogback south of Sierra Blanca. (*See* Sierra Blanca topographic sheet.) North of town and east of the peak by the same name, the formation caps mesas and forms gentle slopes of low cuestas. Anywhere a single layer of Finlay may be exposed for several hundred square yards. Everywhere the joints have been widened by solution, so that on dip slopes the joint blocks stand apart like large paving blocks separated by narrow gutters.

Climatic data are incomplete. The rainfall at Sierra Blanca was recorded continuously for 5 years between 1891 and 1896. Average

annual rainfall during this time was 9.45 inches, over half of which fell in the months of July, August, and September. The long record at El Paso, situated about 75 miles northwest of Sierra Blanca, shows a comparable average precipitation of 8.7 inches annually over a period of

FIGURE 1.—*Map of Texas*
Showing location of Sierra Blanca.

70 years. Taking an average of 52 years, Daingerfield (1931, p. 6) determined that El Paso has 51 days per year when precipitation exceeds 0.01 inch. Apparently Sierra Blanca has about the same number of days a year when the solution effects of meteoric water are active on surficial rocks.

Joint blocks of the Finlay in the Sierra Blanca area show three fundamental types of solution sculpture. These features will be discussed as solution pits, solution facets, and solution furrows.

ACKNOWLEDGMENTS

In assembling data for this paper the writers had the critical comment of several geologists. Professor Kirk Bryan is responsible for the excellent suggestion that has led to the illustration of solution features by contour maps. Professor C. L. Baker has generously contributed a bibliography on foreign literature treating of solution sculpture. Discussion of the problems of solution weathering with Professor M. P. Billings and Professor H. A. Meyerhoff has done much to clarify the ideas presented in this paper.

SOLUTION PITS

TERMINOLOGY

"Solution pit" is here used to include basinlike depressions produced by corrosion on exposed rock surfaces. Excluded are depressions formed by the collapse of rock over cavernous openings as well as depressions which are notably elongate: trough-, channel-, or shaftlike. The definition does not exclude pits formed beneath large bodies of water or those which might originate below the surface of the ground, although they are not discussed in this paper.

Solution pits of several orders of magnitude occur on limestone around Sierra Blanca. Small saucer- or bowl-shaped pits from a fraction of an inch to 1½ inches across are common. In places these pits are closely spaced, the divides are narrow and sharp, and the rock has a pocked appearance. Lahee (1931, p. 32) has described and figured profiles through pits of this general size and has noted enlargement by coalescence.

The largest and most conspicuous types of solution pits around Sierra Blanca Udden (1925) called "etched potholes" or "tinajitas." To these special attention is directed in this paper.

TINAJITAS

General features.—Tinajitas are shallow, floors are relatively level, and walls are steep or overhanging (Pl. 1, fig. 1). Many examples have been illustrated by Udden (1925) and by King (1927).

In contrast to the smooth floor the walls are irregular and may show intricately fretted sculpture. Most tinajitas tend to be circular or elliptical in plan, although some have angulate margins. Tinajitas are shallow, with the mean width generally exceeding five times the length.

The more expansive pits are found where joints or similar natural depressions bound relatively large blocks. The largest example described by Udden (1925, p. 7) measured 10 feet long, 7 feet wide, and 2 feet deep, but in the Sierra Blanca area they are smaller because of the smaller average size of the joint blocks.

Generally the wall has a notch which determines the highest level at which water can stand.

The features above described are illustrated in Figure 2, contour sketch of a small tinajita on Flat Mesa, north of Sierra Blanca. This example occupies the greater part of the surface on a rectangular joint block of Finlay limestone. During heavy rains a small notch in the wall along the upper left margin of the block conveys spillwater out of the pit.

Distribution—Tinajitas occur in dry as well as in relatively well watered regions and have been found on sedimentary and igneous rocks

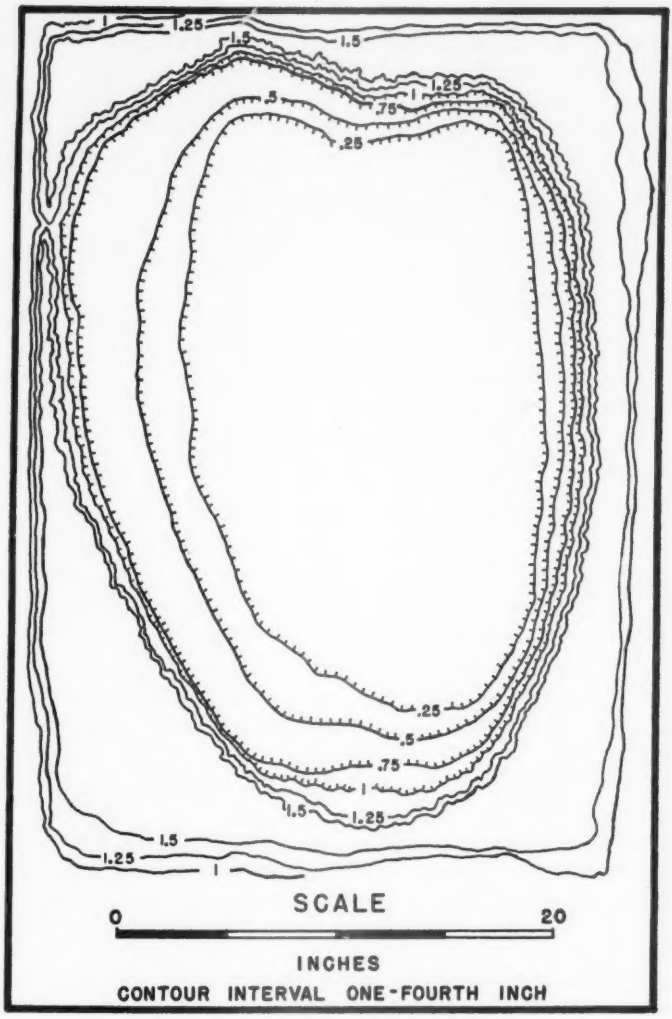

FIGURE 2.—*Contour map of a tinajita*

of several types. Apparently, the only distributional factor common to the various examples pertains to inclination of slope; tinajitas are best developed on flat surfaces or on slopes of less than 3 degrees.

Most tinajitas which have been described or which the writers have seen in the field occur on dense, relatively homogeneous limestone. Such examples on Cretaceous strata in Texas have been cited by Udden (1925) and by King (1927). Around Sierra Blanca tinajitas are found on several limestone formations belonging to the Permian and Cretaceous.

That tinajitas are not restricted to limestone was emphasized by Udden (1925, p. 9), who mentioned examples on granite in Mason County, central Texas, and on various intrusive rocks of Brewster County, Trans-Pecos Texas. A recent personal communication from R. M. Huffington states that tinajitas occur on syenite in the Quitman Mountains a few miles west of Sierra Blanca.

The average annual rainfall at the localities where these tinajitas have been observed ranges from approximately 9 inches around Sierra Blanca to slightly more than 33 inches in the vicinity of Austin, Texas (Sprague, 1926, p. 3). As it is not certain that the solution pits in these various areas were formed under the present climatic conditions, however, nothing can be concluded regarding limits precipitation may set on the distribution of tinajitas.

On part of the southern slope of Devil Ridge, 6 miles south of Sierra Blanca, tinajitas are etched into almost horizontal joint surfaces, which have formed steplike ledges on a hillside sloping approximately 20 degrees. Here it is the slope of the surface of the limestone block, not the slope of the hillside, that controls the development of the solution features.

Origin.—The origin of the depressions from which tinajitas develop need not be considered here; doubtlessly many are initial irregularities on surfaces, and others may be secondary, such as might be produced by groundwater solution before the rock was exposed at the surface. The problem, then, is to account for the way in which an initial depression on a relatively level rock surface might be etched into a tinajita.

The enlargement of a depression into a tinajita can occur only as rock materials are removed from the depression and transferred away from its margin. For soluble rocks like limestone this can be accomplished in several ways.

First, an initial depression may fill with water during showers and overflow, during which process materials dissolved from the bedrock will be removed; consequently the depression is enlarged both laterally and vertically. The depression may be flushed once or many times during a single shower. This process probably predominates in the early developmental stages of all tinajitas but operates less frequently as the depressions become more capacious. Generally the lowest point around the

FIGURE 1. SOLUTION-PITTED JOINT BLOCKS, FLAT MESA
Tinajitas on dip slope less than 3 degrees.

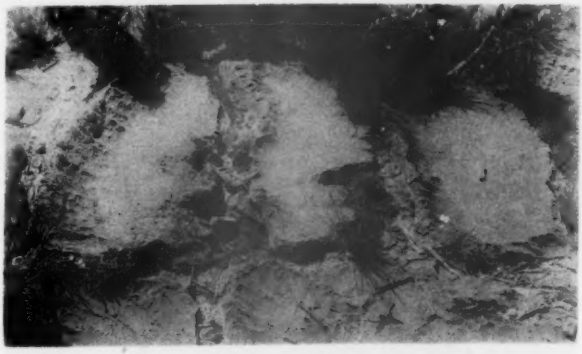

FIGURE 2. SOLUTION-FACETED JOINT BLOCKS, FLAT MESA
On dip slope of 5 degrees.

FIGURE 3. SOLUTION-FURROWED JOINT BLOCKS, DEVIL RIDGE
On dip slope of 20 degrees.

SOLUTION EFFECTS ON FINLAY LIMESTONE

FIGURE 1. NESTED TINAJITAS, FLAT MESA

FIGURE 2. BROAD SOLUTION FACETS, FLAT MESA
Foot rule in joint gutter.

FIGURE 3. FACETS PITTED WITH SMALL TINAJITAS, FLAT MESA
On dip slope of 3 degrees.

rim of the initial depression will serve as a spillway from the first and will be deepened as the depression is etched deeper. Thus, in spite of the growing capacity of the pit, the development and downward growth of an overflow notch will tend to keep the decanting process active, inasmuch as overflow can occur through the notch during rains that could not have filled the depression to the level of its original rim.

Secondly, material dissolved from the floor and walls of an initial depression may be redeposited within the depression upon evaporation of the pool left standing after rains. Subsequently this redeposited material may be flushed out of the depression in suspension or solution during the next heavy rain or it may be blown out by the wind as has been suggested by King (1927, p. 637). White films of caliche, redeposited calcium carbonate, were seen on the sidewalls and on the bottoms of some of the tinajitas around Sierra Blanca. Where the caliche forms a film closely adhering to the rock it could be removed only with great difficulty by the wind. Where, however, the caliche is deposited on the floor around grains of sand and silt—insoluble residues of the bedrock or particles blown into the depression from without—it is likely that the wind could remove these particles along with their coatings of caliche. Whirlwinds, or "dustdevils", might be effective in lifting solid particles from solution pits.

It is evident from this analysis that initial depressions on soluble rock could be enlarged as a result of (1) overflow of water containing dissolved bedrock materials, and (2) removal of evaporites, such as caliche, either redissolved and removed by overflow, suspended in water and removed by overflow, or suspended in air and removed by the wind. To what relative extents these various processes are active in the production of solution pits is not known. Judging by the fact that nearly all tinajitas have well-marked solution notches in their rims regardless of the degree to which they may be exposed to or sheltered from the wind, it seems that removal of dissolved material in overflow water is the dominant process in their development. It remains to account for the distinctive features of tinajitas: their relatively flat floors, subcircular outlines, and steep irregular walls.

Assume that at the time a joint block of homogeneous limestone becomes exposed to the weather it has on its upper surface a slight depression. Rain falls on the block and fills the shallow depression to overflowing. The overflow water spills out of the depression by way of the lowest point in the rim and runs over the margin of the joint block, carrying with it dissolved limestone. As the rock is homogeneous and the depression is in process of active flushing, approximately equal decrements of rock will be taken from all points below water level. Conse-

quently as the pit grows, its newly acquired profiles at any instant are roughly concentric with the original one; thus the concave floor of the pit becomes flatter as it becomes deeper. In like manner the removal of mutually concentric decrements of limestone from around the margin of the depression tends to eliminate the ragged edges and to form a more regular margin of elliptical or subcircular pattern. Where the solvent action of overflow water is concentrated at the lowest place in the rim of the depression an overflow notch is developed and maintained.

Etching can continue beneath the water left standing in the depression after rains, as it is unlikely that initially this pool would be saturated with material dissolved from the rock. As the level of the pool is lowered by evaporation, solvent action on the upper parts of the sidewalls would be inhibited, whereas the lower parts of the walls would be etched until the water became saturated. The result is that the lower parts of the walls would retreat more rapidly than the upper parts. With continuation of this process the walls would become vertical or overhanging. During final stages in the evaporation of the pool it is unlikely that the floor of the depression would be deepened, as the water left standing on it would be concentrated with dissolved material. Precipitation of this material is completed with the disappearance of the pool, and the precipitates may later be removed in one of the ways already mentioned.

Therefore, the process of etching beneath standing pools of water could account for steepening of the sidewalls of the initial depression. This has the effect of making the bottom flatter around the periphery.

At the beginning of each shower, during the initial stages of filling, water will trickle down the steep sidewalls in small rills. As later shown in this paper the effect of such rills is to produce furrows on the limestone. If the tinajita walls are undercut and overhanging, the rills will reduce the overhanging portion to an irregular fretwork.

In like manner to the corrosive processes described two or more initial depressions could coalesce and produce a single tinajita. The writers hope to present in another paper experimental data on solution weathering to test this hypothesis for the origin of tinajitas.

Destruction.—Tinajitas are destroyed when the overflow notch cuts down to or below the level of the floor, when the bottom of the pit is etched through the lower surface of a joint block, when the floor or sidewalls become cracked, or when for any other reason the depression can no longer contain water. Broken tinajitas were described by Udden (1925, p. 9) and may be found on any surface where these solution pits abound.

Nested tinajitas.—If a tinajita wall is breached, it may happen that the deepest part of the tinajita is not next to the overflow notch (Fig. 2). In that instance the deeper portion will pond water, and a new tinajita will form below the level of the old, so that a terraced effect results (Pl. 2, fig. 1).

Udden (1925, p. 9) noted that in some examples of nested tinajitas the new or lower floors were parallel to the upper or older floors, whereas in other cases the lower intersected the upper at some angle. In the second instance it is evident that the block had become tilted since the formation of the older tinajita. Thus, nested tinajitas may be used as criteria to indicate the stability of the blocks into which they are sunk.

SOLUTION FACETS

TERMINOLOGY

A solution facet is an essentially plane surface produced by corrosion. Udden (1914) and Bryan (1929) have described solution facets on exposed surfaces of limestone pebbles, cobbles, and boulders situated on terraces and pediments. Bryan has concluded that solution-faceted pebbles are found only in arid or semiarid regions, where they are restricted to slopes or flats of considerable antiquity.

The facets described in this paper occur on the upper surfaces of limestone joint blocks. Accordingly they are larger than those previously described, some of the larger facets covering as much as 30 square feet of rock surface.

FACETED JOINT BLOCKS

General features.—Where dip slopes developed on layers of jointed limestone are inclined from 3 to 6 degrees the joint blocks have the characteristic surface sculpture shown on Figure 2 of Plate 1 and Figure 2 of Plate 2. At the upslope margin of each block is an upstanding crest, which is sharp, irregular, and unsymmetrical, with the upslope side nearly vertical and the downslope side concave. The vertical wall is essentially coincident with the joint surface at the upper margin of the block. The concave downslope wall is generally creased with parallel furrows whose long axes trend with the slope. A few inches downslope from the crest the concave slope merges with an essentially plane surface which extends to the lower margin of the joint block and slopes in the same direction as the surface of the block. The configuration of a typical block of this sort is shown in Figure 3, a contour sketch made at Flat Mesa, north of Sierra Blanca. In this example the block is roughly square, bounded on all sides by gutterlike depressions formed where joints have been widened. The sharp contrast between the upslope crest and the down-

slope facet is striking. The dip of the limestone at this locality is 5 degrees, whereas the inclination of the facet is slightly over 1 degree. In general the facets are less steeply inclined than are the limestone beds themselves.

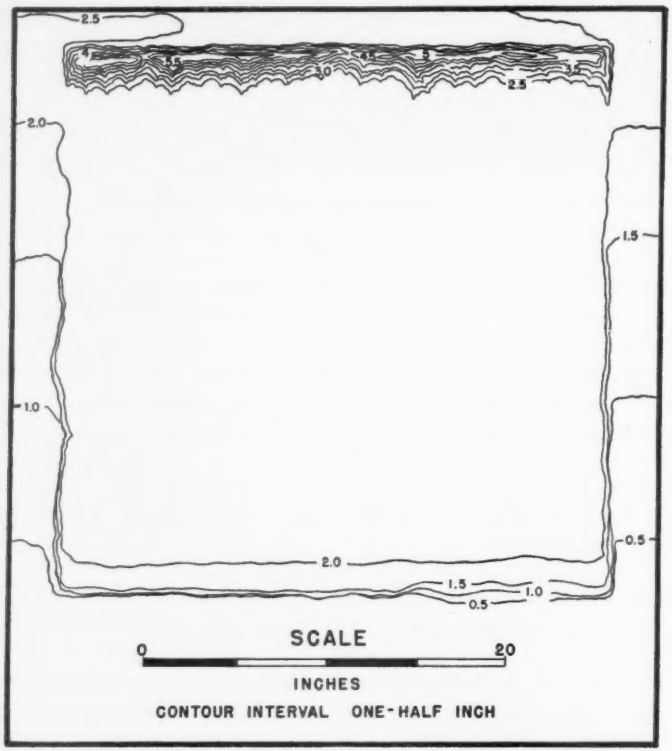

FIGURE 3.—*Contour map of a solution-faceted joint block*

Distribution.—Faceted blocks of the kind described are common on the Finlay limestone in the Sierra Blanca area and occur on the Campagrande limestone in the nearby Finlay Mountains. More observations are needed to determine whether this type of solution sculpture is restricted to any particular type of rock or climate.

From the examples observed around Sierra Blanca it is evident that solution-faceted joint blocks do not form on flat surfaces or on dip slopes as steep as 20 degrees. They were found on slopes as low as 3

degrees, and as steep as 6 degrees, although the actual upper limit of development has not yet been determined. The extent to which slope controls the distribution of solution features is shown in Figure 4, a contour map of a portion of Flat Mesa. The area contoured is covered by a single stratum of jointed Finlay limestone. A slight monoclinal flexure is responsible for a change of slope from less than 3 degrees in the area marked A to 5 degrees in the area marked C. In area A joint blocks are covered with tinajitas. In area C joint blocks are faceted. In the transitional area B both pitted and faceted blocks occur; generally the tinajitas indent the surfaces of the solution facets.

Origin.—During showers part of the precipitation falls directly into the joint gutters between the limestone joint blocks and sinks down or flows downslope along them. The remainder falls directly on the upper surfaces of the blocks and runs down these surfaces and into the gutters at their downslope margins. Joint gutters are thus responsible for downward and lateral drainage of gentle dip slopes. Where the gutter system is as effective as it is on the gentle cuesta slopes of the Sierra Blanca area, each joint block is sculptured only by the water that falls directly on it.

Consider the case of a rectangular joint block of limestone surrounded by joint gutters and situated on a dip slope of 5 degrees. When the raindrops hit during a shower they will course down the slope of the block into the gutter at the downslope margin and will dissolve limestone along their paths. All drops that fall on the block will course across the lower portion of the block, whereas only those that fall on the upper margin will etch that portion of the block. Thus the lower surface of the block is etched more rapidly than the upslope margin, which ultimately is left standing as a residual crest, and a solution facet develops across the lower portion. The downslope side of the crest will in time become sufficiently steep to cause the raindrops falling on it to gather into little rills, which may etch small furrows. The surface of the facet, however, is not of sufficient inclination to cause the thin sheets of water flowing over it to form into rills. Moreover, such rills as might form on the faceted portion are free to meander on the gentle slope and might have their courses frequently changed by changes in the angle of fall of impacting water particles as well as by shifts in air currents. Thus a relatively plane solution facet covering all but the steep upslope edge of the block is etched (Fig. 3).

If one may generalize from the occurrences around Sierra Blanca, three conditions must be fulfilled before solution facets of the type described can develop. First, there must be exposed slopes faced with rock that is

more or less uniformly soluble in meteoric water. Second, the inclination of the slope must be sufficient to prevent ponding of water on rock surfaces but not so steep as to cause runoff to gather into rills. Third, the slopes of soluble rock must be provided with gutter systems along joints

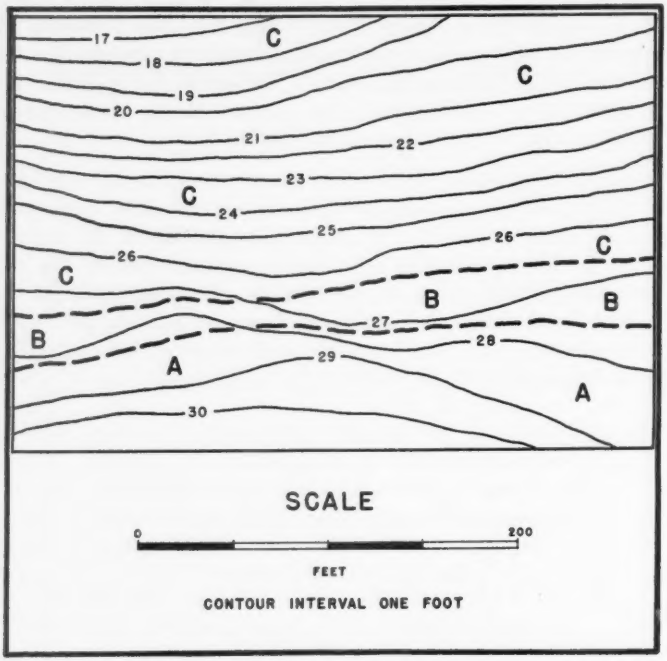

FIGURE 4.—*Map of a portion of Flat Mesa*
A—Area of abundant solution pits.
B—Area with solution pits and facets.
C—Area of abundant solution facets.

or similar natural depressions. These gutters must be sufficient to accommodate the slopewash, allowing each block of soluble rock on the slope to be etched only by the precipitation that falls directly on it. Bare soil-less slopes of soluble rock are more likely to be found in dry than in humid areas, so it is to be suspected that solution-faceted joint blocks, like solution-faceted pebbles, are characteristic of arid and semiarid regions.

Pitted solution facets.—It has been noted that the inclination of a facet is generally less than the inclination of an original bedding plane on a

joint block. The significance of this will be investigated experimentally, but for the present it will be sufficient to note a result of this phenomenon. When a facet of 1-degree slope is formed on a block whose original bedding surface had a dip of 5 degrees, the tendency toward ponding of water on the facet increases as the facet becomes flatter. Ponded films of water on the facets are capable of etching slight depressions, which may grow into tinajitas. Thus are explained the solution-faceted blocks with tinajitas etched into the facets, examples of which are common in area B (Fig. 4) and which are illustrated on Figure 3 of Plate 2. Such blocks epitomize the effect of slope on solution sculpture; their steep upslope fringes are solution-furrowed, their gentler downslope areas are solution-faceted, and the flattest portions of the facets are solution-pitted.

SOLUTION FURROWS

TERMINOLOGY

Solution furrows are linear depressions formed by corrosion. Depending upon their size and geographic distribution solution furrows in rock have been variously designated. Small examples, a millimeter or less across, are to be found on the familiar *Rillensteine,* like those described by Laudermilk and Woodford (1932). Rock surfaces intricately furrowed by corrosion grooves to be measured in inches or feet have been described by Europeans under the names *lapies (lapiés, lapiez, lapiaz), rascles, esserts, laissines, Karren,* or *Schratten* (Cvijić, 1924, p. 27; Kayser, 1909, p. 293-295; Sanders, 1921, p. 593). Of these terms lapies is perhaps the most widely used, although it has been employed in slightly different senses by different authors. Cvijić has defined lapies as surfaces covered by a network of furrows and crests which are chiefly the result of corrosion by meteoric water. This author would restrict the term to apply only to limestone slopes, but other authors have extended lapies to include similar effects of weathering on other types of rock such as sandstone, basalt, and granite (Palmer, 1927; Stearns, 1935; Martonne, 1927; Lapparent, 1906). Whereas some, possibly most, authors apply the term lapies to an entire complex of solution furrows and intervening ridges, others have used "solution groove" and lapies synonymously (Stearns, 1935, p. 59-60). In the following description lapies is used to apply to rock surfaces of any kind on which relatively large solution furrows predominate. Individual linear depressions on lapies are called lapies furrows or simply solution furrows.

LAPIES IN THE SIERRA BLANCA AREA

General features and distribution.—In the Sierra Blanca area lapies were found only on limestone surfaces with inclinations of 20 degrees

or more. The best examples are on the southern slope of Devil Ridge, 6 miles south of Sierra Blanca. Here individual joint blocks of the Finlay limestone, which forms a dip slope of approximately 20 degrees, stand in relief above surrounding solution-widened joint depressions.

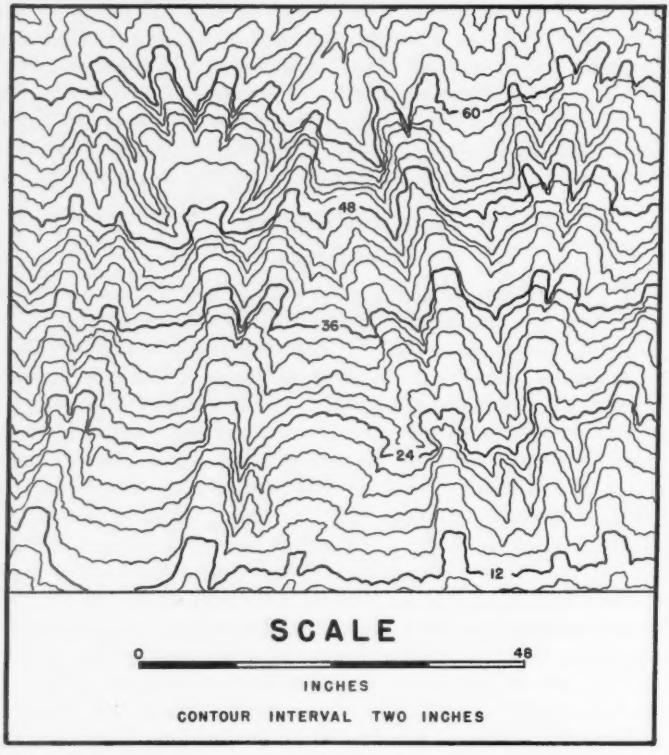

FIGURE 5.—*Contour map of a solution-furrowed joint block*

The surfaces of the blocks are trenched with furrows trending with the dip of the slope. On some blocks the furrows are similar in size, parallel, and so closely spaced that the divides between them are reduced to sharp crests. On other blocks the furrows are of several sizes, the larger ones with pinnate patterns, the smaller ones forming grooves down the slopes of the crestlike divides. The largest furrows observed were about 6 inches across and 8 inches deep.

An example of intricately furrowed limestone is shown on Figure 3 of Plate 1, and a portion of this block is contoured in Figure 5. It is apparent from these illustrations that the crests tend to be serrate and that the furrows are more or less U-shaped in cross section and irregular in longitudinal profile.

Origin.—Lapies in the Sierra Blanca area are the result of the corrosional work of running water. Rain water falling on steep slopes tends to gather into rills which flow down slope with little tendency to meander. These rills corrode the rock and develop solution furrows, which are deepened and widened so that the divides between them stand in relief. Rills flowing down the divides likewise develop solution furrows, and in time the secondary furrows may reduce the divides to sharp irregular crests.

The effects produced by solution on moderately steep to steep slopes may be simulated on correspondingly steep slopes of relatively insoluble rock acted upon by the mechanical processes of erosion. Steep slopes of granite with flutings produced by corrasion have been described by Branner (1896, p. 280, 294) and Matthes (1930, p. 116). Fluted escarpments similar to lapies but produced by rainwash on sand, gravel, and sandstone have been figured by Gilbert (1875, Pl. 1) and by Dobbin and Reeside (1930, Pl. 4).

Comparison with lapies of other regions.—The lapies developed in limestone around Sierra Blanca show no features which have not already been described in other areas, such as Hawaii (Stearns, 1935, p. 59-60; 1939, p. 64-65; Palmer, 1927) and in various parts of Europe (Cvijić, 1924; Kayser, 1909, p. 293-295; Martonne, 1927, p. 168-174). Lapies occur at all altitudes and under various conditions of precipitation. They may be formed by the sporadic downpours of arid regions or by the showers of breaking surf along the Adriatic coast. There seem to be but two prerequisites for their formation: exposed surfaces of rock that will yield to solution by water and slope sufficient to cause runoff to gather into rills.

SUMMARY OF CONCLUSIONS

Joint blocks of limestone exposed in the barren, dry country around Sierra Blanca, Texas, everywhere show the effects of solution by meteoric water. The solution features are of three types: pits, facets, and furrows.

The most conspicuous type of solution pit is the tinajita, a shallow, subcircular, steep-walled, and flat-floored depression which forms only where water can be ponded on rock surfaces. Field evidence indicates that solution pits of this type do not form on slopes of more than

3 degrees. Tinajitas can develop by etching and enlargement of depressions on exposed surfaces as dissolved limestone is removed by overflow during rains. Caliche material precipitated within the pit on the rock walls and floor and about clastic particles on the bottom upon evaporation of the water may be removed from the pit by the wind or it may be flushed out of the pit during subsequent rains.

Solution facets develop on the upper surfaces of limestone joint blocks paving dip slopes of 3 to 6 degrees. These facets are essentially plane surfaces which extend from the downslope margins of individual joint blocks to within a few inches of their upslope margins where each facet merges with a steep concave slope which rises to a sharp crest. As a result of the effective drainage by joint gutters, each block is etched only by the water that falls on it. The downslope portion is etched by all the water that falls on the block, whereas the upslope margin is affected chiefly by the water that falls directly on it; this accounts for more rapid corrosion on the major portion of the block with a residual sharp-crested ridge left at the upper margin. The slope of the surface is not sufficient to cause water running over it to gather into rills; hence the surface is worn down uniformly, and a plane facet develops.

Solution furrows develop on slopes ranging from 20 degrees to the vertical, where the slope is of sufficient steepness to cause runoff to gather into rills under which the solvent action of running water is concentrated. The furrows are characteristically U-shaped in section, vary from a fraction of an inch to several inches in breadth and depth, show parallel or pinnate patterns, and are generally so closely spaced that divides between them are reduced to serrate ridges. They form typical lapies such as have been widely described in European literature.

Although the solution effects described are for a particular type of rock in a limited area, a survey of the available literature indicates that the processes involved in solution sculpturing are generic to slope, not specific to any particular area. The writers have found no mention in the literature of faceted blocks like those described in this paper, but such features are probably common, especially in dry regions. Slope control in the production of furrows is as evident in effects of corrasion as in those of corrosion.

A study of solution weathering may supply data to record the slow and periodic shifting of rocks in response to mass or individual movements of blocks. A block containing a tinajita may shift positions so that the solution pit will no longer hold water; but a new tinajita may form in the bottom of the old, and the angle between the floors of the younger and older pits will record the direction and amount of shift.

Limestone strata capping mesas, cuestas, and hogbacks in the Sierra Blanca area show by their pitted, faceted, or furrowed sculpture that the lowering of dip slopes in this area is effected chiefly by solution. Under prevailing dry conditions this must be an extremely slow process. Bryan has estimated that at least 2000 years would be required for the development of solution facets on limestone pebbles in arid and semi-arid regions. One is inclined to believe that some of the larger solution features in western Texas may likewise be of considerable antiquity. It is to be hoped, therefore, that data on the rate of solution weathering in this and similar regions will be forthcoming in future investigations.

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Agricultural and Mechanical College of Texas, College Station, Texas; Southern Methodist University, Dallas, Texas.

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SHALLOW-WATER GLOBIGERINA SEDIMENTS

BY G. W. CRICKMAY, H. S. LADD, AND J. E. HOFFMEISTER

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ABSTRACT

On Katafanga, Vanua Vatu, and Avea, three small islands in the Lau group of Eastern Fiji, occur highly calcareous Neogene sediments in which the most abundant organic remains are Globigerinidae (about 20 per cent by volume). Less abundant are calcareous red algae (0—2.0 per cent), calcareous blue-green algae (0—5.5 per cent), benthonic Foraminifera (0—4.0 per cent), coral fragments (0—22.0 per cent), echinoid spines (1.0—2.0 per cent), and brachiopods and mollusks (0—6.0 per cent).

An origin in water considerably shallower than that of most Globigerina deposits is indicated by both physical and biological evidence. Diagnostic features are: fragmental oölites; interbedding of thin oölitic layers containing few Globigerinidae with beds rich in Globigerinidae; abundant calcareous mud; and high calcium carbonate content and absence of volcanic material generally present in deep-sea oozes. Biological characters of significance are the presence of fragments of reef corals, blue-green algae, and Crustacea.

The above features and other evidence suggest a depth of more than 40 fathoms—the limit of flourishing reef-coral growth—but a depth not greatly in excess of this figure. Apparently the pelagic shells were brought by surface currents to an area where there was little clastic deposition and a paucity of benthonic forms. Some limestones contain a high percentage of lithified calcareous mud which appears to be similar to muds now accumulating on submarine banks and in certain coral lagoons. It is suggested that the presence of this material inhibited benthonic growth.

The Fiji sediments are compared with deep-sea ooze; the supposed deep-water Globigerina limestones of Barbados, the Solomon Islands, South America; deposits on submarine banks and in the lagoons of existing atolls; shallow-water Globigerina chalk of England; Globigerina "soapstone" of Vitilevu, Fiji; and foraminiferal dune limestone of the Arabian Sea.

INTRODUCTION

Sediments rich in pelagic Foraminifera, mainly Globigerinidae, are known to be accumulating at depths of 500 to 2500 fathoms over an area of 50,000,000 square miles on the floors of existing oceans. They are unknown on the continents, but similar sediments rich in Globigerinidae have been reported from Barbados, the Solomon Islands, and elsewhere.

Limestones rich in Globigerinidae occur on the continents in a number of places, but most of them originated in probably less than 100 fathoms.

Beds of this kind are known in the Upper Cretaceous of England and France and in the Oligocene of Jamaica.

As Cayeux (1935) has pointed out, the presence of Globigerinidae in a sediment is in itself no indicator of depth. Under proper conditions these pelagic remains may accumulate in extremely shallow water or even on a beach. From the beach the wind may carry them inland to form dunes.

In the present paper, Globigerina sediments from the islands of Katafanga, Vanua Vatu, and Avea in eastern Fiji are described. Comparisons are made with similar rocks from other areas and with certain sediments that are accumulating at the present time. Criteria which may be used in distinguishing various Globigerina sediments—abyssal, moderately shallow water, beach, and eolian types—are elaborated.

ACKNOWLEDGMENTS

The Fiji sediments were collected in 1934 by Ladd and Hoffmeister while engaged in a study of the geology of the Lau group under the joint auspices of the University of Rochester and the Bishop Museum of Honolulu. Crickmay studied the limestones microscopically at the University of Georgia. J. W. Sanders, Jr., made chemical analyses at the Georgia School of Technology. Doctors W. A. Setchell, W. Storrs Cole, and Waldo L. Schmitt aided in determining some of the fossils. Dr. C. T. Trechmann kindly furnished a series of specimens from Barbados for comparative studies. The Director of H. M. Geological Survey and Museum, London, loaned four thin sections of Kathiawar rocks collected by J. W. Evans, two of these being cut especially for this purpose. The manuscript has been reviewed by Dr. John B. Reeside, Jr., of the United States Geological Survey.

LOCATION

The locations of Katafanga, Vanua Vatu, and Avea are shown in Figure 1. More exactly, the position of Avea in Northern Lau is 17° 11′ S., 178° 54′ E. From Avea, Katafanga lies 23 miles to the SSE, Vanua Vatu 74 miles to the SSW. All three islands are surrounded by coral reefs whose seaward slopes descend steeply to more than 100 fathoms.

GLOBIGERINA SEDIMENTS OF LAU

KATAFANGA

General geology.[1]—Katafanga is a slightly crescentic, rectangular island a mile long and about one-third mile wide near the western end of an oval lagoon enclosed by a well developed barrier reef.

[1] The general geology of Katafanga, Vanua Vatu, and Avea is given more fully by Ladd and Hoffmeister in a report on the geology of Lau soon to be issued by the Bishop Museum of Honolulu.

As shown on Figure 2 the southeastern and western shores of the island are fringed with coastal flats. A volcanic area, occupying the southeast quarter of the island, comprises andesite flows, partly agglomeratic.

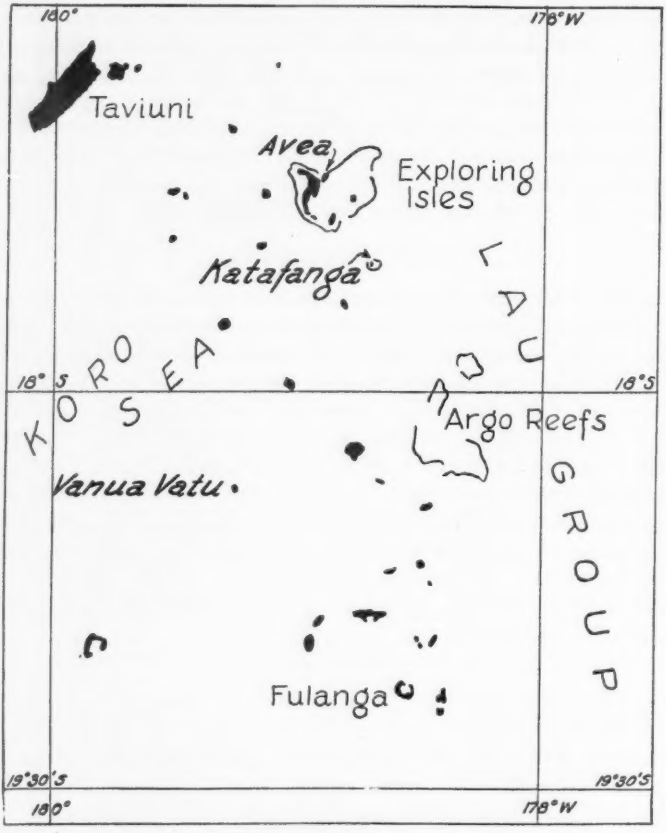

FIGURE 1.—*Outline map showing location of islands*

Limestones overlie the andesites, and in several places their basal members contain volcanic debris. Exposures of the contact are found at many levels, for the contact surface dips at various angles. This suggests an erosional unconformity, but not necessarily an appreciable time interval.

The limestones vary considerably in general appearance and in organic constitution. The prevailing type is hard and gray to pink with abundant

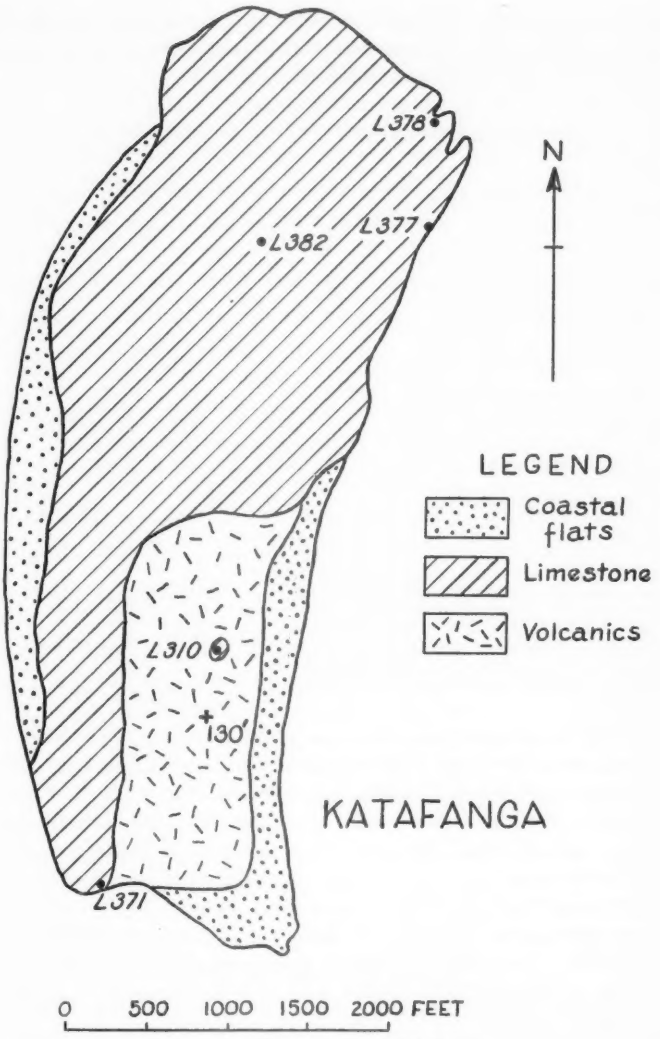

FIGURE 2.—*Sketch map of Katafanga*

organic remains, of which Foraminifera are most common. Algae are inconspicuous except in a white crystalline limestone at Station L382. Corals are rare rock formers but are present at Station L310 in a hard,

porous, silicified rock. Volcanic debris is abundant at Station L371 in a foraminiferal limestone. Globigerina limestones were obtained at Stations L377 and L378 on the northeast coast (Fig. 2).

TABLE 1.—*Organic content of Globigerina sediments*

	1	2	3	4	5	6	7
Algae, red	pr.	....	1.0	1.5	....	2.0	....
Algae, green	.....	....	....	5.5	....	....	....
Pelagic Foraminifera	53.10	19.0	20.0	1.0	30.0	15.0	41.0
Benthonic Foraminifera	2.13	2.0	2.0	2.0	....	4.0	0.5
Other calcareous organisms	9.24	2.5	8.0	1.0	1.0	24.0	5.0
Siliceous organisms	1.64	....	....	....	....	....	....
Unidentified	.....	3.5	5.0	18.0	1.0	6.5	1.0
Total organic constituents	66.11	27.0	36.0	29.0	32.0	54.5	47.5
Minerals and volcanic fragments	33.89	....	....	....	68.0	....	52.5
Calcareous paste		73.0	64.0	....		....	

1—Average Globigerina ooze, CHALLENGER collection (from Twenhofel).
2—Katafanga, Fiji. Station L377. Globigerina limestone.
3—Katafanga, Fiji. Station L378. Globigerina limestone.
4—Katafanga, Fiji. Station L378. Oölite.
5—Avea, Fiji. Station A19. Reworked tuff.
6—Vanua Vatu, Fiji. Station L505. Calcareous sandstone.
7—Barbados. Average of two specimens from Oceanic series.

Petrography.—Globigerina limestone collected immediately above sea level at Stations L377 and L378 on Katafanga is aphanitic, pale pink to light brown, and bedding is only roughly indicated by thin, irregular, white layers, in part oölitic. It is hard, compact, and breaks with a smooth to subconchoidal fracture. It is made up of organic remains—which for the most part can be recognized with a hand lens—in a very fine-grained calcareous "paste" apparently similar to the calcareous so-called "amorphous material" in the Upper Cretaceous chalk of eastern England. The paste consists of calcite in grains averaging about 3 microns in diameter and in thin section is distinctly gray brown, in places almost opaque.

The organic constituents of the rock are shown in Table 1. Brachiopods and mollusks are more abundant at Station L378, but, as the proportions were determined from one thin section, small differences may be due to selection of specimens. The complete shells of Globigerinidae predominate (Pl. 1, fig. 1). Most of the shells are granular calcite, evidently

mold filling, but a few are represented by original fibrous calcite in radial arrangement. Less abundant are calcareous red algae, beach and larger Foraminifera, echinoid spines, brachiopods, and mollusks, all rarely fragmental. Larger fossils, present but not seen in thin section, include pteropods and a crustacean, probably a shallow-water species.

TABLE 2.—*Chemical analyses of Katafanga limestone*

Analyses by J. W. Sanders, Jr.

	L377	L378
Moisture	.29	.26
Insoluble	.38	.38
R203	.72	.76
Calcium carbonate	65.82	65.78
Magnesium carbonate	32.66	32.90
Loss on ign	.29	.31
Total	100.16	100.39

The limestone at Station L378 contains thin, white, distinctly oölitic layers. The oölites are shell fragments, averaging 0.5 mm. in diameter, rimmed by only 0.1 mm. of granular calcite with faint concentric structure. The fragmental character of the organic remains prohibits identification (Table 1). Calcareous green algae (*Halimeda*) are the commonest fossils, but red algae, beach and pelagic Foraminifera, and echinoid fragments are present. A cement of secondary calcite with distinct radial structure (Pl. 1, fig. 2) surrounds the oölites, the margins of which are marked by a dust line. A few of the oölites are fragmental. The oölitic rock contains none of the dark calcareous paste which makes up about 65 per cent of the Globigerina limestone.

The very small insoluble residue obtained from the Globigerina limestone at Station L378 consists of silicified shells and spicules. No siliceous organisms, such as Radiolaria, were found.

Chemical analyses.—Chemical analyses (Table 2) show about 98.5 per cent carbonates. The specimen from Station L377 is essentially unaltered, and thus the high dolomite suggests primary deposition. Lemberg's solution proved unsatisfactory for distinguishing the dolomite from calcite, presumably because of its extremely fine grain. All the secondary carbonate filling molds and other cavities is calcite.

VANUA VATU

General geology.—Vanua Vatu is somewhat isolated on the western fringe of the Lau group. It is subquadrate with an average diameter of

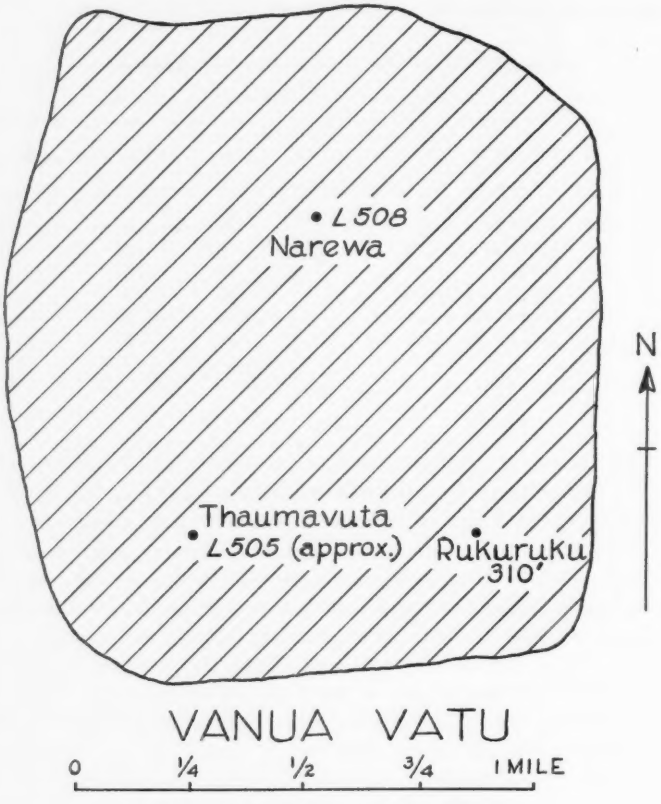

FIGURE 3.—*Sketch map of Vanua Vatu*

1½ miles (Fig. 3). It is encircled by a close-set barrier reef tied to land at several points on the west but extended to leeward (northwest) as a hook-shaped loop.

The limestone which makes up the island is widely exposed on the coastal flats as well as in the higher ground, and the island is, therefore, appropriately named Vanua Vatu—"Land of Rock." The higher eleva-

tions lie along the windward portion of a rocky rim that encircles the island near the coast.

The limestone is hard, compact, and white, gray, or pink. It is essentially unaltered, although some appears crystalline because of granular calcite filling cavities and irregular veinlets. A foraminiferal type from Station L508 consists mainly of larger and beach type Foraminifera in a very fine, dark, calcareous paste.

Petrography.—Globigerina limestone occurring at Station L505, about 300 feet above sea level, is a hard, pink, finely crystalline calcarenyte consisting mainly of coral (?) detritus and Foraminifera. Pelagic Foraminifera, represented by molds, constitute about 15 per cent, and the larger and beach types about 5 per cent. Fragments making up 22 per cent are altered to crystalline calcite and closely resemble altered coral from other islands of the group. They are separated from the cementing granular calcite by dust lines. No volcanic material and very little calcareous paste is present (Pl. 1, fig. 4). The cementing calcite is crowded with small rhombic euhedral crystals (about .02 mm. in longest dimension), probably dolomite. This pure carbonate rock is a moderately well sorted sand cemented by carbonates, but, like most of the limestones of the Lau islands, exhibits no distinct stratification. The crystalline appearance of the hand specimen is not due to recrystallization but rather to infiltration of granular calcite and dolomite as a cement.

AVEA

General geology.—Avea, in the north-central part of the Exploring group at the northern end of Lau, is small and elongate. Its northeast-southwest longer axis is 1⅔ miles long, and its greatest width, found near its center, is two-thirds of a mile (Fig. 4). Its abrupt coastal slopes culminate in a high central limestone ridge nearly coextensive with the longer axis. The maximum elevation is about 600 feet.

Avea is composed of both volcanics and limestone, the latter predominating. The volcanics are composed of bedded andesite tuffs, agglomerates, and basalt flows. The tuffs vary in texture both vertically and horizontally. The limestone lies directly on the volcanic rock. Contacts show a rounded volcanic surface.

At Station A19, near sea level on the southwestern coast, the tuffs are rich with pelagic Foraminifera, particularly Globigerinidae.

Petrography.—The specimen from Station A19 is a very light grayish-brown to white, friable, calcareous "tuff" with dark spots. Thin sections reveal organic remains and vitric and crystalline volcanic fragments in calcareous clay. The organic remains include pelagic and beach Fora-

minifera, echinoid spines, and Bryozoa (?); the Globigerinidae are by far the most abundant (30 per cent by volume). The rounded to angular rock fragments are mainly glass, partly altered and strongly stained by iron oxides, containing acicular feldspar. Feldspar (andesine) also

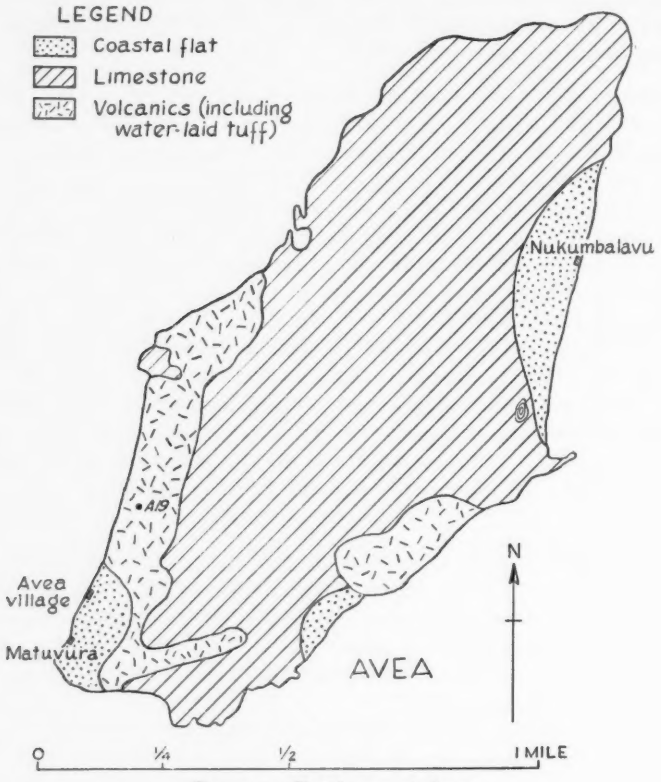

FIGURE 4.—*Sketch map of Avea*

occurs in separate crystals with rarer hornblende and pyroxene. The rock is not a true pyroclastic but consists of reworked volcanic material cemented with calcium carbonate (Pl. 1, fig. 3).

COMPARISONS WITH OTHER GLOBIGERINA SEDIMENTS

DEEP-WATER DEPOSITS

Recent Globigerina ooze.—Globigerina ooze of the deep sea is well known, and a brief summary of characteristics will suffice. It is made up

mainly of Globigerinidae,[2] with a small proportion of calcareous algae, mollusks, and other shells. Siliceous organisms, such as Radiolaria, are generally present in small amount. Most oozes contain innumerable coccoliths and rhabdoliths, respectively spherical and rod-shaped bodies of algal origin less than 0.1 mm. in diameter.

Deep-sea oozes generally contain more than 15 per cent insoluble material which consists mainly of volcanic dust, both mineral fragments and palagonitized glass. Most of them are white to brown or pink, but those near land are gray with terrigenous clay. The calcium carbonate content decreases generally with depth, apparently due to increased solution. Many of the shells in Globigerina ooze show signs of solution and are commonly reduced in thickness.

Table 1 shows the average mechanical analysis of 118 samples of Globigerina ooze collected by the CHALLENGER Expedition, as given by Twenhofel (1932, p. 294).

Oceanic series of Barbados.—The island of Barbados is made up of three series of rocks. The basal series, called the Scotland group, consists of steeply folded, shallow-water Eocene beds. These are overlain unconformably by the Tertiary[3] Oceanic series, which includes Globigerina marls and radiolarian earths. This in turn is overlain by Pleistocene and Recent coral rock.

The Oceanic series is 350 to 2000 feet thick and is generally believed to represent deposits in 1000 to 3000 fathoms. Schuchert (1935, p. 709), in a recent review of the evidence, agrees with this figure and states that the sediments of Barbados

> ". . . do not merely show a 'resemblance' to those of the present oceanic deeps, but are actually like them; the contained fossils are also in the main of abyssal types, and since there is an absence of submarine cliffs and very steep slopes, he is led . . . to agree with Blanford and Vaughan, who hold that the depth at which the Barbados oozes were formed was at least five thousand feet."

The upper part of the series exposed on Bissex Hill is thought by Trechmann (1937, p. 384) to represent moderately shallow water beds, for here is found a marly, clastic, fragmental limestone containing bivalves and terebratulids. Elsewhere the upper beds contain a layer made up mainly of *Amphistegina* for which Trechmann postulates a depth of probably less than 30 fathoms. Other fossils listed by Trechmann are: worm tubules, calcareous algae, Bryozoa, echinoderm tests and spines, small simple corals, *Callianassa* claws, and sharks' teeth.

Bather (1934, p. 799-874) also reviewed the evidence bearing on depth, with particular reference to the fossil echinoderm *Chelonechinus crassus*.

[2] Murray and Renard (1891, p. 213-223) designate as Globigerina oozes those which contain more than 30 per cent of carbonate of lime, chiefly the shells of Foraminifera.

[3] These beds have been variously assigned to late Oligocene, Miocene, and Pliocene.

He concluded that this depth is not abyssal but probably exceeds 500 fathoms. Bather further described another species belonging to the same genus, *C. suvae*, from the "soapstones" of Vitilevu, Fiji, which he believed indicated a depth of 150 to 250 fathoms.

Trechmann (1937, p. 348) is in doubt whether *C. crassus* was obtained from the Oceanic beds, or from the overlying coral rock. Ladd (1936, p. 301-302) has recently shown by other evidence that the "soapstones" which contain fossils of this genus in Fiji were probably deposited in waters only slightly exceeding 50 fathoms.

In a detailed comparison of the Globigerina rocks of Barbados with the Globigerina chalk of the Paris Basin, Cayeux (1935, p. 28-29) notes in the Barbados rock more mineral grains, more colloidal silica, much more clay, abundance of Radiolaria, thicker shells of Foraminifera, and larger coccoliths.

Four thin sections of the Barbados rocks, made from specimens supplied by C. T. Trechmann, have been examined during the present study. Two of these—one from Chimborazo in the interior (Pl. 2, fig. 1), and one from Bissex Hill near the top of the section—contain an average of 41 per cent Globigerinidae. The chambers are commonly separated and empty; echinoid spines are unusually abundant (4 per cent); the organic remains are cemented by dark calcareous clay. Also at Chimborazo a radiolarian earth contains very rare Globigerinidae, many siliceous spicules, and rare mineral grains (mainly quartz) in very fine calcareous clay (Pl. 2, fig. 2). At Bath Beach, southeast Barbados, a friable tuff is made up almost entirely of brown glass shards and rare mineral grains.

The Globigerina rocks of Barbados differ from those of Katafanga and Vanua Vatu in that the latter contain less Foraminifera, pure calcareous mud in place of terrigenous clay, and no radiolarian earths. The Barbados rocks differ from the "tuffs" of Avea and Vitilevu in that the "tuffs" show considerable lateral variation and contain water-worn grains of volcanic material and diagnostic shallow-water fossils.

Globigerina limestones of Solomon Islands.—Guppy (1887a; 1887b) reported the occurrence of foraminiferal limestones from the Solomon group and interpreted them "as the *consolidated foraminiferous oozes* of the 'CHALLENGER' and other Expeditions." Two types of Globigerina rock were recognized—those containing both pelagic and bottom-living Foraminifera and those containing only pelagic forms.

The first type, according to Guppy, is soft and friable to hard and compact limestone containing algae, mollusks, corals, echinoderm fragments, and Foraminifera. It is reported to occur on Treasury Island and on Alu, the largest island of the Shortland subgroup, where it overlies soft pteropod limestone. On the island of Ugi, similar foraminiferal

limestones contain abundant volcanic detritus and clay. Guppy believed these sediments were deposited at a depth somewhat exceeding 150 fathoms because of the abundance of Foraminifera and the absence of massive corals. Guppy noted that, except for the presence of corals, the limestones are commonly very similar to the English chalk, which, at the time he wrote, was held by many to be a deep-sea deposit.

In the second type of Solomon Island limestones recognized by Guppy, the Globigerinidae are by far the commonest organic remains. These rocks were reported to occur in the Florida subgroup where they are associated with coral limestone and on Treasury Island to the northwest where the soft and friable rock displays a regular stratification. A similar but much altered limestone occurs on Piedu Island, near Treasury. This rock, according to Judd (Guppy, 1887a), "exactly resembles many chalks in structure". These beds are regarded by H. B. Brady (Guppy, 1887a, p. 95) as deposits of considerable depth, possibly from 200 to 1800 fathoms. A friable brown tuff containing Globigerinidae and manganese nodules occurring on Santa Ana is compared by Guppy to deep-sea clay of 2000 fathoms.

The Globigerina limestone of Poperang, in the Shortland subgroup, in places contains abundant brachiopods, simple corals, mollusks, and volcanic material. This rock was interpreted to be a shallow-water deposit because of the presence of mollusks and brachiopods, but it is interesting to note that aside from these constituents the rock differs but little from limestones believed to have formed at great depth.

In summary, the sedimentary formations of the Solomon Islands are in part similar to those of the Lau Islands. Guppy believed that the rocks rich in Globigerinidae represented deposits at considerable depth—150 to 2000 fathoms—because of the abundance of pelagic Foraminifera and paucity of other forms, particularly corals. This evidence is by no means conclusive, and the writers believe that a correct evaluation of depth of deposition must await a more complete study of the paleontology and petrography of these rocks. The close comparisons drawn between some of the Solomon Island limestones and the English chalk lead one to suspect a much shallower depth of deposition than that postulated by Guppy. Guppy's report was prepared shortly after the publication of the CHALLENGER reports and with the advice of Sir John Murray.

La Luna limestone and equivalent beds in South America.—In northern South America Globigerina limestones are more widespread than in any other part of the world. They are Cretaceous and have been described in some detail by Hedberg (1931a). In northern Venezuela the limestones are included in the La Luna formation. The typical La Luna rock is dark and is composed in large part of the tests of small pelagic

Foraminifera. Cavities of the tests are generally filled with clear crystalline calcite, the surrounding matrix being chiefly dark carbonaceous or bituminous material. The rock contains little or no coarsely crystalline calcite, sand grains, or silt. Approximate analyses of five samples from as many localities showed from 42.33 to 94.64 per cent of calcium carbonate. In some places the recognizable calcareous foraminiferal remains constitute as much as 90 per cent.

In his original paper Hedberg (1931a, p. 243) stated that "The La Luna rock would seem to have all the qualities of a consolidated *Globigerina* ooze were it not for the profusion of organic matter . . ." In a discussion of this paper (1931b) he reiterates his belief that the original sediment must have been a Globigerina ooze but expresses the opinion that it was formed in water of moderate depth rather than in the greater depths where such sediments are accumulating today. He points out that the La Luna formation occurs in Colombia (Villeta formation) and in eastern Venezuela (Guayuta formation)[4] and states that

"The distinctive character of the rock is thus not the product of any particular local environment, but is the result of conditions of deposition which must have prevailed during a part of the Cretaceous throughout much of northern South America and possibly neighboring regions for a sufficient length of time to permit the deposition of from 500 to 3,000 feet of limestone."

In eastern Venezuela, according to Hedberg, the type section of the Querecual formation is almost identical with the La Luna of western Venezuela and totals 2420 feet in thickness. Hedberg (1937, p. 2015-2016) believes that it was laid down in a maximum Cretaceous transgression that probably took place in late Middle Cretaceous time. He states that

"In the deeper portions of the seaway, clastic sediment was at a minimum, and peculiar conditions, probably due to hindrance to the free circulation of the marine waters, resulted in the preservation of immense quantities of organic matter and pelagic Foraminifera on bottoms which were only rarely favorable for benthonic animal life."

SHALLOW-WATER DEPOSITS

Muds of existing banks and atolls.—Globigerinidae are known to occur sparsely in many deposits at less than 100 fathoms. Thorp (1935) has found their tests in many calcareous muds at less than 15 fathoms in the Florida-Bahama area, but generally in very small numbers. Pelagic Foraminifera, according to Thorp (1935, p. 57), are locally brought into shallow water by "changing tides and currents, sweeping through passages between Keys."

A moderately shallow deposit of greenish-gray mud containing abundant Globigerinidae is reported by Sir John Murray (Gardiner, 1931, p. 133) to occur in Suvadiva lagoon in the Maldives of the Indian Ocean.

[4] In a more recent paper Hedberg (1937) defines the Querecual formation as being roughly equivalent to the "Guayuta" formation of Liddle.

The deposit is accumulating at a depth of 40 fathoms and deeper on a bottom which has practically no surface fauna.

Globigerina marls ("soapstones") of Vitilevu, Fiji.—The marls of the Neogene Suva formation are soft buff to gray and well bedded.[5] They are fine-grained and earthy, being made up chiefly of clay from weathered volcanic rocks mixed with considerable calcareous foraminiferal tests. They are most widely developed in the valleys of two of the larger streams, the Rewa and the Mba; in the Suva district close to the mouth of the Rewa the marls have an exposed thickness of 500 feet. In describing a typical specimen as seen with very high power under convergent light Pegau (1934, p. 44) noted that

". . . the material is doubly refracting and appears to be calcite intermixed with variable amounts of sericite and kaolinite and dotted with grains of magnetite and limonite. In the matrix are included numerous cross sections of foraminifera that range in diameter from 0.1 to 0.5 mm. The shells are made up of a very fine-grained calcite and are filled with the matrix material. There are also spherical bodies of calcite that exhibit a uniaxial cross under crossed nicols."[6]

Two examples of marls from the Suva area were sent for examination to the Imperial Institute in England. A report, originally published in the Bulletin of the Institute, is quoted by C. H. Wright (1916, p. 13) in a paper describing the soils of Fiji.

"The two samples were similar in appearance and character. They . . . may be classed as marls. They consisted of volcanic dust containing felspar, hornblende, magnetite, and mica, together with a considerable quantity of the remains of calcareous and siliceous organisms; some unbroken foraminifera occurred in both samples.

"Chemical examination . . . gave the following results:—

	'A' per cent	'B' per cent
Fe_2O_3	5.40	7.54
Al_2O_3	12.08	16.49
CaO	19.24	12.77
MgO	6.95	5.78
K_2O	1.23	1.64
Na_2O	1.23	2.72
NiO	trace	trace
SiO_2	30.41	38.56
P_2O_5	trace	trace
H_2O+CO_2	23.28	14.32
Total	99.82	99.82"

[5] For more complete descriptions of the "soapstone", its distribution, *see* Ladd, H. S., *et al.* (1934).

[6] The spherical bodies of calcite mentioned by Pegau are probably tangential sections of Globigerinidae.

The Foraminifera are very abundant locally; Cushman (1934) identified 95 species from samples from one locality, Station 371 (Pl. 1, figs. 5, 6). Many of the marls contain pteropods, but other fossils are rare. They include large echinoids (Bather, 1934), barnacles (Withers, 1934), limpets, tubes of mud-boring mollusks, various plant remains (tree ferns, nutmegs), sharks' teeth, and a bird's egg (Ladd, *et al.*, 1934). Opinions differ as to the depth of water in which the Globigerina marls were deposited.

The samples studied by Cushman (1934) were particularly rich in Lagenidae, and this fact, judging from similar Recent faunas from the Philippines, indicated a depth of 100 to 250 fathoms. Bather (1934) weighed all types of evidence and concluded that the sediments were probably laid down in water not less than 150 fathoms deep and possibly much deeper. The barnacle from the marl was identified by Withers (1934) with a Recent Malayan species taken from a depth of more than 285 fathoms. Ladd cited the occurrence of reef corals in original positions of growth in a lenticular mass of limestone included in the marls. These suggested a depth of not more than 50 fathoms. Ladd's shallow-water hypothesis also accounted for the general distribution of the Globigerina-rich layers in the marl facies of the Suva formation. This facies is best developed near the windward southeast coast. Ladd (1936, p. 301-302) expressed the opinion that the formation as a whole was laid down in waters which, locally at least, did not exceed 50 fathoms, and that during periods of unusually heavy weather many pelagic Foraminifera were washed in to form an occasional Forminifera-rich layer.

Upper Cretaceous chalk of England.—In their classic papers on the Upper Cretaceous series of eastern England, Hill and Jukes-Brown (Hill, 1886, 1888; Hill and Jukes-Brown, 1886; Jukes-Brown and Hill, 1887) have described poorly stratified limestone and chalk rich in Globigerinidae and very fine-grained calcium carbonate "amorphous material", possibly a chemical precipitate (Tarr, 1925). The "amorphous material" is apparently similar to the calcareous "paste" of limestones of Katafanga. Globigerinidae, mainly represented by separated chambers, make up 20 per cent, and other organic constituents, largely fragmental, make up 8 to 10 per cent of a specimen from Norfolk. This rock contains 70 per cent "amorphous material". Quartz and other minerals are rare, and volcanic detritus is absent. In chalky phases the organic remains are said to be rarely fragmental, although prismatic rods resulting from the breakdown of mollusk shells are locally common.

Analysis of a specimen from Lincolnshire by Hill showed 93.5 per cent carbonates, of which less than 1 per cent is reported to be magnesium

carbonate. Hill found that part of the insoluble residue is glauconite, which commonly replaces the Globigerina shells. The general lack of bedding and sorting, together with the character of the fossils, led Jukes-Brown and Hill to conclude that the Globigerina rocks are deep-water deposits. Present opinion, however, is that the chalk is a moderately shallow water deposit.

Globigerina sediments from other areas.—Globigerina limestones have been reported from a number of islands in the East Indies. Some are considered to be Cretaceous, but, according to Umbgrove, this is doubtful and nothing whatever is known about their stratigraphic connections. Examples cited by Umbgrové (1938, p. 21) include: island of Letti, in Miocene breccias of Schubert; Tanimber Islands, Obi, and the Soela Islands, reported by Brouwer; and the northern arm of Celebes, reported by Schubert. Molengraaff (1913, p. 693) states that on the island of Timor the oldest Pliocene deposits are pure Globigerina limestone. Because of the absence of terrigenous material he believes that it was formed in an open but not necessarily deep sea far from land. He states that petrologically it bears a remarkable resemblance to the white chalk of Europe and suggests that it may have had a similar origin.

Globigerina limestones of moderately shallow water origin are also reported by Cayeux (1935) from Morocco, Spain, France, and Crete; Grabau (1924, p. 454) cites Globigerina limestone from Malta and Schuchert (1935, p. 422-424) notes an occurrence in Jamaica. David (1900, p. 6) states that such a rock was collected by Danvers Power in New Caledonia.

Mawson (1905) records the existence of tuffs containing Globigerinidae on several islands in the New Hebrides, particularly on the island of Efate, where fine-grained beds have all the essential characters of the Fiji "soapstone". They are more widespread than all other outcropping formations, except the limestone. He believes they represent deposits of the finer submarine pyroclastics. Contemporary pelagic Foraminifera were interbedded. Mawson does not estimate the depth at which they were formed but states that they contain no interbedded coral limestone.

Globigerina tuffs similar in some ways to those of Avea and Vitilevu, Fiji, have also been reported from the Solomon Islands (Guppy, 1887a; 1887b) and from Tonga (Hoffmeister, *et al.*, 1932).[7]

LITTORAL AND EOLIAN DEPOSITS

Recent deposits.—Beach sands, partly or mainly Globigerinidae, occur in Trinidad (Twenhofel, 1932, p. 165). It is generally believed that such

[7] A section of a calcareous tuff from Eua, Tonga, is also given by Harker (1935, p. 259).

deposits are due to oceanic currents contributing pelagic shells to slowly accumulating terrigenous sediments. Beach deposits, rich in Foraminifera, have in places been reworked by wind. In this class belong the calcareous sands of Dogs Bay, Galway, Ireland (Welch, 1898, p. 80; Wright, Joseph, 1895, p. 252-253).

More rarely this process works in the opposite direction. Shallow-water Foraminifera and other light shells may be blown from the beach out to sea and thus become incorporated in the deep-sea ooze. This explanation is offered by Norton (Thorp, 1935, p. 57) for the occurrence of shallow-water species in a Globigerina ooze from Tongue of the Ocean, Bahamas, from a depth of 825 fathoms. It should be noted, however, that only moderately fine material can be so transported.

Foraminiferal dune limestone of Kathiawar.—Cross-bedded limestone, probably Pleistocene, occurs about 30 miles inland from the present margin of the Arabian Sea (Evans, 1900; Chapman, 1900). According to Evans, organic calcareous particles, mainly Foraminifera (Globigerinidae are very rare), are cemented with granular calcite (Pl. 2, fig. 3). Many of the Foraminifera have a thin coating of calcium carbonate seemingly deposited on their surfaces before they came to rest in the dune (Pl. 2, fig. 4). Oölites are rare. The formation has been compared by Evans to the deposits of Dogs Bay (Ireland), Bermuda, Canary Islands, and St. Helena.

Wind-blown foraminiferal deposits of Kathiawar differ from the limestones of Fiji. They lack calcareous mud, their organic particles are uniform in size, and their bedding is more distinct and of the dune type. The foraminiferal rocks of Kathiawar rest unconformably on underlying Deccan traps.

EVIDENCE OF DEPTH OF DEPOSITION

PHYSICAL EVIDENCE

Carbonate content.—The calcium carbonate content of Globigerina ooze is generally less than 90 per cent and averages only 64.47 per cent according to Vaughan's compilation from the CHALLENGER Report (Twenhofel, 1932, p. 285-287). Vaughan has also shown that calcareous deposits averaging over 90 per cent calcium carbonate are generally of moderately shallow water origin. The bottom samples collected by Thorp (1935) from the Florida-Bahama region showed that 75 per cent had more than 90 per cent carbonates.

The Katafanga Globigerina limestones contain an average of 98.5 per cent carbonates, thus differing from most deep-sea oozes. The limestone of Vanua Vatu is also pure carbonate. On the other hand, the Globigerina "tuff" of Avea is estimated to contain not over 30 per cent

carbonates, and the Globigerina "soapstones" of Vitilevu contain about 10 to 40 per cent carbonates, although these are considered to be of shallow-water origin. Thus, while a very high carbonate content appears to be indicative of moderately shallow water, not all Globigerina sediments of this depth are so characterized.

Calcareous mud.—The calcium carbonate content of deep-sea oozes is almost entirely organic, for these sediments are said to contain very little of the fine-grained "lime" muds so characteristic of many shallow-water deposits. The sediments of the Bahama Banks according to Thorp (1935, p. 109-113) contain an average of 26.7 per cent calcareous mud (less than .05 mm.), and a few samples contain more than 65 per cent.

The Katafanga and some of the Vanua Vatu limestones contain abundant calcareous mud (60-72 per cent). The Globigerina limestone on Vanua Vatu is, however, a cleanly washed sand. The presence of calcareous mud is in itself, probably, an uncertain indicator of depth for little is known of its distribution. The writers, nevertheless, believe that the presence of a large percentage of these fine-grained carbonates, as in the limestones of Katafanga, is suggestive evidence of moderately shallow water. The so-called abyssal limestone of Barbados also contains much calcareous mud, but this is mixed with terrigenous material and does not compare closely with the mud of the Katafanga limestones. This distinction has previously been pointed out by Cayeux (1935, p. 29) in his comparison of the Barbados rock with the chalk of the Paris Basin.

Oölites.—Calcareous marine oölites (Brown, 1914; Twenhofel, 1932, p. 757-769) may be restricted to shallow water, but little definite information is available. Although there is no agreement on their origin, it is generally believed that they result from precipitation of calcium carbonate around some nucleus. This implies deposition from sea water saturated with calcium carbonate, a condition which is not attained in the deep sea. Oölites, as far as the writers can learn, have never been recorded in depths exceeding 100 fathoms and are probably restricted to a very much shallower depth. Oölitic beds are usually associated with shallow-water formations. For these reasons, the oölitic bed in Globigerina limestone of Katafanga is of considerable interest. This oölite is of a peculiar type since the precipitated calcium carbonate forms a thin rim around a large organic fragment, similar apparently to the oölitic grains in the dune limestone of Kathiawar. The oölites, however, are cleanly washed and probably are not of eolian origin.

Insoluble residue.—Insoluble residues from deep-sea ooze contain siliceous organisms (spicules of sponges, Radiolaria, Foraminifera, and diatoms), minerals (feldspar, hornblende, magnetite, and others), and

finely divided material (volcanic dust). These generally total more than 5 per cent; the average for 118 samples collected by the CHALLENGER expedition is reported as 35.53 per cent (Cayeux, 1935, p. 24).

Volcanic material, consisting of fragmental minerals and palagonitized glass, is also a common constituent of some shallow-water Globigerina rocks. Thus the "soapstones" of the Suva formation of Vitilevu contain grains of feldspar, magnetite, and other minerals. Many of these grains may represent original pyroclastic material thrown directly into the sea by explosion, but it appears that most of the material in the "soapstone" has been transported. Locally this type of marl contains well-rounded volcanic boulders and worn coral heads. The fact that the typical "soapstones" are best developed in the valleys of two of the island's major streams is, likewise, suggestive of transportation. The "soapstones" grade laterally into tuffs. These relations have been described elsewhere (Wentworth and Ladd, 1931).

Mawson (1905, p. 454) reports that the "soapstones" of Efate in the New Hebrides invariably contain volcanic glass and pumice and, in small quantities, feldspar grains; particles of magnetite and pyroxene are accessory minerals.

The "tuff" of Avea is similar to some of the "soapstones" of Vitilevu. Most of the volcanic grains and the fragmental minerals are rounded, due, it is believed, to the action of subsurface currents reworking the loose pyroclastic material rather than to long transportation as in the case of the "soapstones" of Vitilevu. Grain size varies considerably in the "tuff" of Avea but not in typical Globigerina ooze. The Globigerina rocks of Katafanga and Vanua Vatu are at once distinguished from abyssal deposits by their complete lack of volcanic detritus. They also lack Radiolaria and other siliceous tests. The insoluble residue from these limestones is extremely small and contains only a few siliceous spicules.

Structural and textural variations.—The Globigerina "tuffs" of Avea and the "soapstones" of Vitilevu show good cross-bedding in places, but the Globigerina limestone of Katafanga and Vanua Vatu show little trace of bedding.

Not much is as yet known about the characteristic bedding of deep-sea ooze. Bradley (1940, p. 97-109) and his associates have studied a number of cores of sediment taken from the ocean bottom by means of the Piggot core drill. Promising as this work is, it has just begun and "the cores already studied are but pin points of light in an abyss of darkness." Marked horizontal and vertical gradation of sediments is taken as characteristic of most littoral and shallow-water deposits. The Suva forma-

tion is characterized by marked lateral variation in texture, composition, and paleontology. The Globigerina sediments on Katafanga, Vanua Vatu, and Avea appear to have a restricted distribution, passing laterally and vertically into sediments that contain few pelagic Foraminifera. These features suggest shallow-water origin.

Associated rocks.—The rocks associated with Globigerina deposits in some cases indicate depth of deposition better than the deposits themselves. Association of Globigerina ooze with red earths, radiolarian ooze, or pteropod ooze would indicate depth, and, except for the absence of pteropod ooze, such an association is known in Barbados. Globigerina deposits containing conformable layers of reef rock can hardly be interpreted as deep-sea deposits, for this would imply alternate uplifts and subsidence of the ocean bottom of 3000 to 15,000 feet. The presence of lenses of limestone in the "soapstones" of Vitilevu, one of which contains reef corals *in situ*, indicates moderately shallow depth of deposition, locally, at least, not exceeding 50 fathoms.

Summary.—In summary, physical characteristics indicating moderately shallow depths are: high calcium carbonate content, largely calcareous mud; presence of oölites; absence of siliceous organisms; marked horizontal gradation; conformable interbeds known to be of shallow-water origin.

These characteristics are not all present in any one Globigerina rock, but generally one or two taken with the organic evidence is sufficient clue to depth of deposition.

It is to be noted that Globigerina ooze of deep-sea origin can be recognized more by the absence of these characteristics than by its own diagnostic features.

It is not certain that all three Lauan occurrences accumulated at the same depth, but it is believed that all three were formed in waters considerably shallower than those in which typical Globigerina oozes are accumulating today. The Avea deposit was, perhaps, formed at greater depth than were the Globigerina limestones of Katafanga and Vanua Vatu, but it is doubtful if the depth over Avea greatly exceeded 50 fathoms.

BIOLOGICAL EVIDENCE

The relative proportions of various pelagic organisms in the open ocean are said to be somewhat similar from place to place, and the ratio of coccoliths to pelagic Foraminifera in deep-sea Globigerina ooze is everywhere very similar. Sediments which contain a relatively high proportion of coccoliths are thought, therefore, to have been deposited in shallower waters where surface currents have contributed many pelagic

forms. Such currents may well effect a separation of the coccoliths from the relatively larger Globigerinidae. No coccoliths have been recognized in thin sections of the Globigerina rocks of Fiji, either in Lau or in Vitilevu.

Under certain conditions the occurrence of reef corals is significant evidence of depth because these organisms do not grow in profusion below 40 fathoms, and no living colony—so far as we know—has ever been dredged from below a depth of 50 fathoms. If it can be shown that the coral heads are *in situ* the sediments containing them are clearly of shallow-water origin, but this is difficult even when large areas of well-preserved fossil material are exposed. The presence of an occasional upright head or the occurrence of abundant coral debris suggests shallow water, but it must be remembered that coral heads and finer coral debris can be rolled to considerable depths down the relatively steep sides of isolated islands or reef patches.

ENVIRONMENT OF DEPOSITION OF GLOBIGERINA ROCKS IN LAU

GEOLOGICAL HISTORY

Before attempting to consider the depositional environment of the Globigerina limestones it appears desirable to outline briefly the known geological history of Katafanga and Vanua Vatu. Both are small islands rising from depths of probably several hundred fathoms. Soundings made close to the islands indicate that the upper portions of their submarine slopes rise steeply, for the 100-fathom line hugs the seaward edge of the existing surface reefs. Available data clearly suggest that both islands represent isolated volcanic centers. On Katafanga the volcanic foundation is widely exposed below a cap of younger limestone, but on Vanua Vatu similar limestones conceal any postulated volcanic core.

On Katafanga the igneous core is a mixture of agglomerates and flows, and the mound was apparently built up from the sea floor by explosive eruptions. After the last eruption the cone was almost up to, or possibly above, sea level. Currents and waves effectively attacked the unconsolidated pyroclastics of the growing cone. The windward (southeast) portion was leveled to a submarine platform. Shells of shallow-water organisms mingled with the reworked volcanic materials to form a thin veneer of tuffaceous limestone that eventually blanketed much of the volcanic foundation; limestones formed subsequently were free of volcanic material. The exact date of the volcanic activity is not known, but the limestones of both Katafanga and Vanua Vatu appear to be late Tertiary.[8] Limestone deposition on Katafanga was interrupted by one or more ele-

[8] W. Storrs Cole, who has studied larger Foraminifera from Katafanga, states that the evidence as to age is not conclusive but that, in his opinion, the limestone is probably upper Tertiary. More significant forms were obtained on Vanua Vatu, and the limestones from that island appear definitely to be Lower Miocene (Tertiary *f* of the East Indian section).

vations which brought the island well above sea level. Subsequent erosion has removed the limestone cover on the windward side of the island.

The geological history of Vanua Vatu is not well known, but it is believed that the main steps were similar to those recorded on Katafanga. It may be mentioned, in passing, that many other islands in the Lau group had a similar history.

ENVIRONMENT OF THE GLOBIGERINA BEDS

The Globigerina limestones of Katafanga and Vanua Vatu apparently were formed under somewhat unusual conditions because rocks of this type are rare in Lau. During an extended field season several hundred outcrops were sampled, and many more were examined. Only four showed abundant Globigerinidae. Detailed lithologic studies reveal, however, that the Globigerina limestones differ from the other calcilutites in one single respect—namely, the abundance of Globigerinidae.

It is recognized that concentrations of any pelagic Foraminifera can accumulate only in areas relatively free from (1) concomitant clastic sedimentation and (2) abundant benthonic life. Under these conditions, the Globigerina deposit may be formed at any depth up to 2500 fathoms.

Vanua Vatu provides no evidence that any part of the cone projected above sea level while the Globigerina limestone was deposited, hence, there was apparently no source for terrigenous sediments. On Katafanga the leeward portions of the mound may have projected above sea level, but, if so, any debris was carried to leeward for none is present in the Globigerina rocks or other near-by limestones. Fragments of reef corals in the limestone, however, indicate that parts of both Katafanga and Vanua Vatu extended to within 50 fathoms of the surface.[9] Shoals almost certainly existed because, in addition to the corals already mentioned, all undetermined organic materials and some of the oölites are fragmentary.

The second condition necessary for the accumulation of Globigerina limestone—namely, the lack of abundant benthonic life—is influenced by various factors, chiefly depth, adequate food and light, and suitable bottom conditions. Available evidence indicates that the Fiji Globigerina rocks were laid down at moderate depths where sufficient food and light would be available to benthonic organisms. The most important factor influencing the amount of benthos in Katafanga seems to be the type of bottom. The fine-grained calcareous "paste" of the Katafanga Globigerina rocks represents a lithified calcareous mud. Similar material is found in many

[9] Fragments of reef corals up to 8 inches in diameter were seen in the limestone of Katafanga. These corals were not seen in position of growth, but their size is such that a local source is clearly indicated. No elevated coral reefs have been found on the island, hence it is not certain that reefs ever flourished there. The occurrence of a few coral fragments in the limestone may merely record sporadic growth of individual colonies on the higher portions of the submarine mound.

of the limestones of Lau. Where present in large quantities the limestones almost invariably contain some Globigerinidae and a paucity of benthonic forms. Presumably the fine calcareous mud was ill-suited to most types of benthonic life. In a few places, where the configuration of the submarine mound was favorable, surface currents brought large quantities of pelagic Foraminifera, and these were deposited with the calcareous mud. In other mud-covered areas only a few organisms, such as algae and echinoids, were included in the deposit.

The occurrence of large quantities of Globigerinidae in the limestone of Vanua Vatu is less easy to understand, for it is clastic and contains very little calcareous "paste." It is composed of fairly well sorted sand grains cemented by carbonates. It must have accumulated very slowly, and the configuration of the bottom must have been such as to allow surface currents to bring abundant pelagic Foraminifera.

The concentrations of Globigerinidae in the "tuff" of Avea appear to be similar to those described from Vitilevu in western Fiji. The fine, reworked, tuffaceous material inhibited benthonic life, and, as elsewhere, the Globigerinidae accumulated slowly.

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UNIVERSITY OF GEORGIA, ATHENS, GEORGIA; U. S. GEOLOGICAL SURVEY, WASHINGTON, D. C.; UNIVERSITY OF ROCHESTER, ROCHESTER, N. Y.

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EXPLANATION OF PLATES

PLATE 1. LIMESTONE, SANDSTONE, AND "SOAPSTONE"

Figure

1. Globigerina limestone from Station L378, Katafanga, showing Globigerinidae, brachiopods embedded in calcareous "paste."
2. Oölitic limestone from Station L378, Katafanga, showing cleanly washed oölites cemented with calcite.
3. "Tuffaceous" limestone from Station A19, Avea, showing fossils, and rounded volcanic grains (V) embedded in a dark calcareous clay. Globigerinidae (G), echinoid spines (E).
4. Coral sandstone from Station L505, Vanua Vatu, showing coral fragments (C), echinoid spines (E), larger Foraminifera (LF), and pelagic Foraminifera (G) cemented with coarse calcite (Ca). Coral fragments surrounded by thin rim of dolomite rhombs (D).
5. "Soapstone" from Suva formation from Station 371, Vitilevu, showing pelagic Foraminifera (G) and mineral and volcanic grains (M) in fine calcareous clay.
6. "Soapstone" from Suva formation from Station 371, Vitilevu, showing abundant pelagic Foraminifera in dark calcareous clay. Globigerinidae in both cross and tangential section.

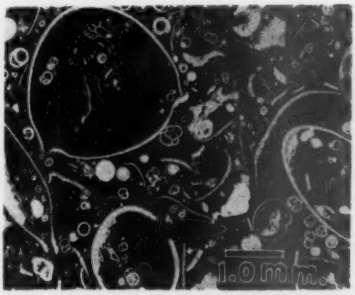


FIGURE 1

FIGURE 2

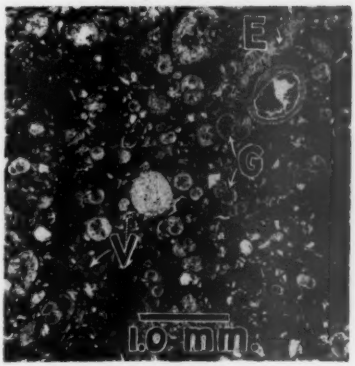
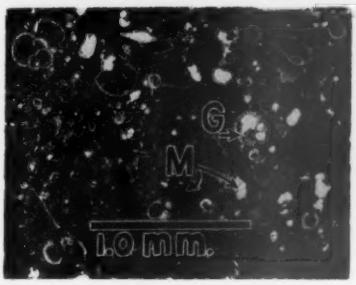


FIGURE 3

FIGURE 4



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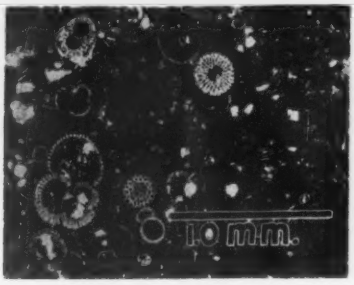
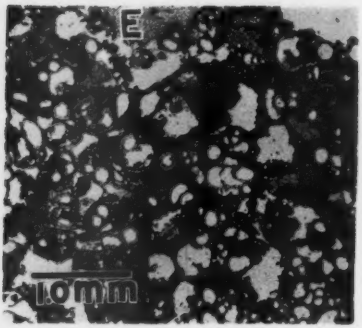


FIGURE 6

LIMESTONE, SANDSTONE, AND "SOAPSTONE"



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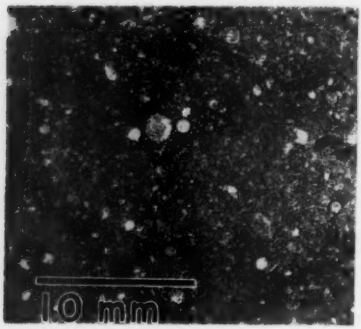


FIGURE 2

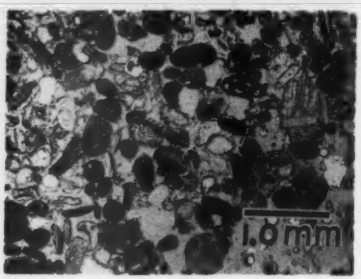


FIGURE 3

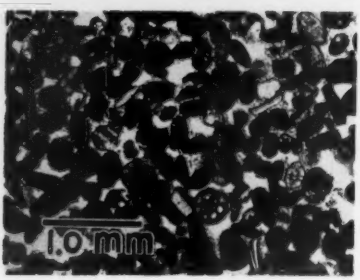


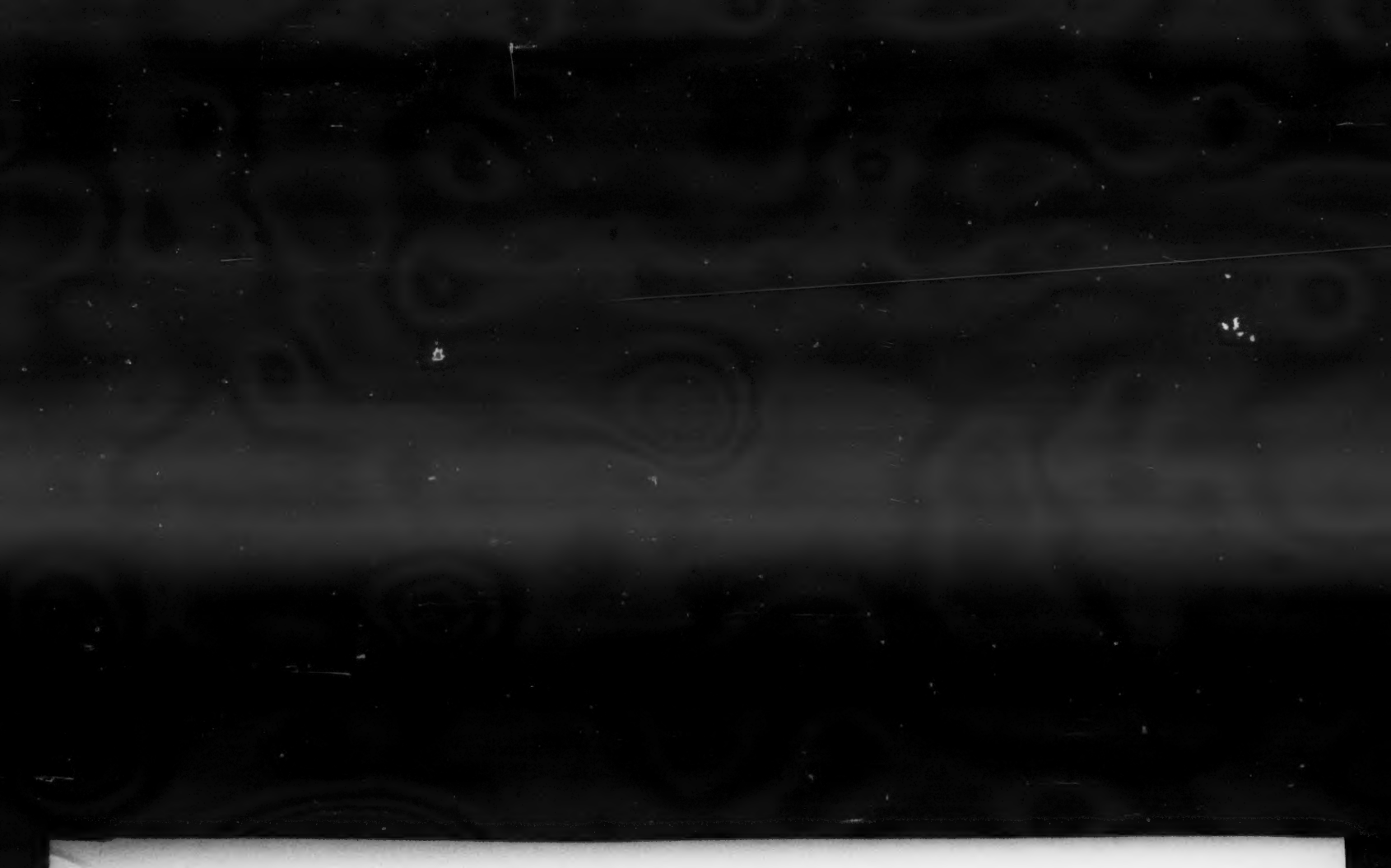
FIGURE 4

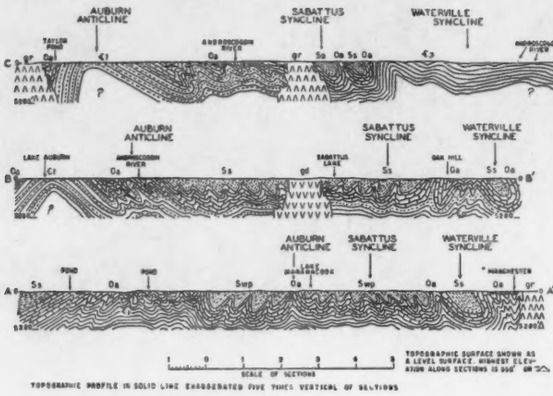
OCEANIC SERIES AND DUNE LIMESTONE

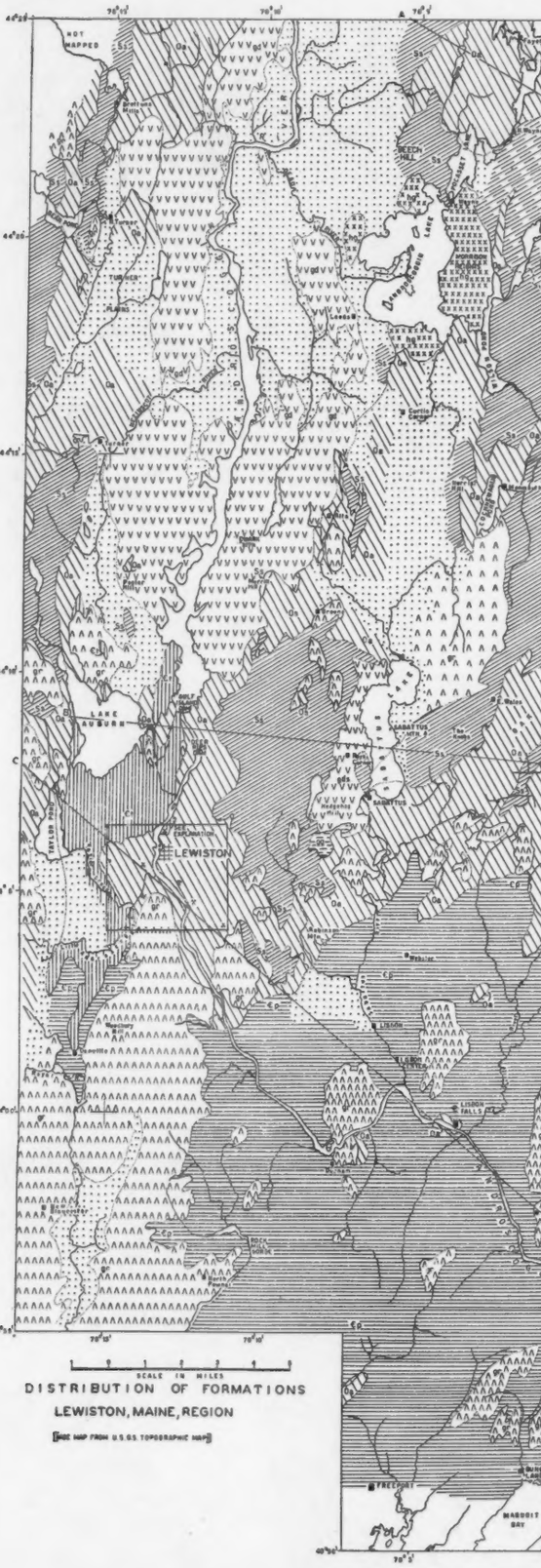
PLATE 2. OCEANIC SERIES AND DUNE LIMESTONE

Figure

1. Oceanic series from Chimborazo, Barbados, showing echinoid fragments (E) and abundant Globigerinidae embedded in dark calcareous clay and cemented with granular calcite. Original label states this specimen may belong at base of overlying coral reef rock.
2. Oceanic series from Chimborazo, Barbados, showing Radiolaria embedded in dark clay. White circular areas are Radiolaria unfilled with clay.
3. Calcareous dune sandstone from half a mile southwest of Khalilpur, about 30 miles from the sea, containing wind-blown beach materials, including Foraminifera, cemented with calcium carbonate.
4. Calcareous dune sandstone from Kathiawar containing calcareous fragments and pelagic Foraminifera cemented with carbonates.



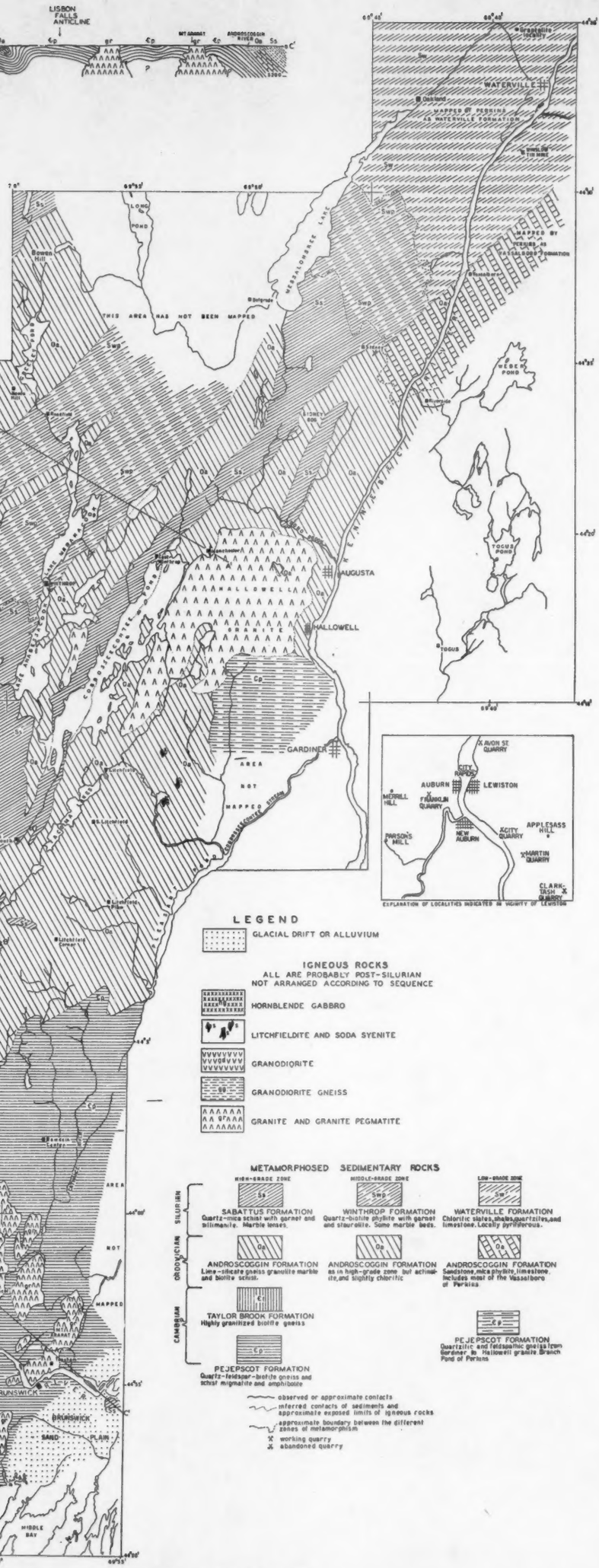

AUBURN ANTICLINE
SABATTUS SYNCLINE
WATERVILLE SYNCLINE
SCALE OF SECTIONS
TOPOGRAPHIC PROFILE IN SOLID LINE EXAGGERATED FIVE TIMES VERTICAL OF SECTIONS



DISTRIBUTION OF FORMATIONS
LEWISTON, MAINE, REGION

[INDEX MAP FROM U.S.G.S. TOPOGRAPHIC MAP]

DISTRIBUTION OF FORMATIONS IN



LEGEND

GLACIAL DRIFT OR ALLUVIUM

IGNEOUS ROCKS
ALL ARE PROBABLY POST-SILURIAN
NOT ARRANGED ACCORDING TO SEQUENCE

- HORNBLENDE GABBRO
- LITCHFIELDITE AND SODA SYENITE
- GRANODIORITE
- GRANODIORITE GNEISS
- GRANITE AND GRANITE PEGMATITE

METAMORPHOSED SEDIMENTARY ROCKS

	High-grade zone	Middle-grade zone	Low-grade zone
Silurian	**Sa** SABATTUS FORMATION — Quartz-mica schist with garnet and sillimanite. Marble lenses.	**Swd** WINTHROP FORMATION — Quartz-biotite phyllite with garnet and staurolite. Some marble beds.	**Sw** WATERVILLE FORMATION — Chloritic slates, shales, quartzites, and limestone. Locally pyritiferous.
Ordovician	**Oa** ANDROSCOGGIN FORMATION — Lime-silicate gneiss granulite marble and biotite schist.	**Oa** ANDROSCOGGIN FORMATION — as in high-grade zone but actinolite, and slightly chloritic	**Oa** ANDROSCOGGIN FORMATION — Sandstone, mica phyllite, limestone. Includes most of the Vassalboro of Perkins.
Cambrian	**Ct** TAYLOR BROOK FORMATION — Highly granitized biotite gneiss		**Cp** PEJEPSCOT FORMATION — Quartzitic and feldspathic gneiss from Gardiner to Hallowell granite. Branch Pond of Perkins.
	Cp PEJEPSCOT FORMATION — Quartz-feldspar-biotite gneiss and schist migmatite and amphibolite		

observed or approximate contacts
inferred contacts of sediments and approximate exposed limits of igneous rocks
approximate boundary between the different zones of metamorphism
working quarry
abandoned quarry

TIONS IN THE LEWISTON, MAINE, REGION

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
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STRUCTURE AND METAMORPHISM OF LEWISTON, MAINE, REGION

BY LLOYD W. FISHER

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ABSTRACT

Five mappable units have been established in an area formerly mapped as pre-Cambrian in southwestern Maine. The geologic column from oldest to youngest is as follows: the Cambrian Pejepscot quartz-feldspar-biotite gneiss and schist; the Taylor Brook gneiss; the Cambro-Ordovician Androscoggin lime-silicate gneiss, marble, and biotite schist; and the Silurian Sabattus quartz-mica-sillimanite schist and the Winthrop chloritoid phyllite. All are former sedimentary rocks.

Large igneous bodies, including granite, granodiorite, gabbro, syenite, and pegmatite, and their associated dikes, are regarded as late Paleozoic.

Correlation of the Sabattus formation with the middle Silurian Waterville shales, 50 miles northeast of Lewiston, is suggested. An attempted correlation, southeastward across the general strike from Lewiston into an area previously mapped as Carboniferous, indicates either a Paleozoic age for this area or a possible erosional interval between the early Paleozoic and the Carboniferous formations.

INTRODUCTION

LOCATION

The area described includes approximately 700 square miles, most of which is in Androscoggin County in southwestern Maine (Fig. 1). Field studies were centered on the Lewiston quadrangle. The work deals principally with sedimentary rocks in the high-grade zone of metamorphism and their less metamorphosed equivalents.

PREVIOUS WORK

Little detailed geologic mapping has been done in this part of Maine. Jackson (1839) made some general reconnaissance studies throughout the State and mapped most of the rocks of the immediate region as Montalban. Greenstone in the Androscoggin River between Lewiston and Auburn was described by Stephenson (1839, p. 191). The camptonite dikes in the vicinity of Lewiston were described by Merrill (1892, p. 49). Bastin (1911) made a more detailed study at Lewiston; he concluded that the gneisses and schists are dynamically metamorphosed sediments. Bastin's purplish-gray mica schists are classified with the Androscoggin formation of this paper.

Landes (1925) described in detail the pegmatites of the Mount Apatite region west of Lewiston but did not discuss their age. Papers by Katz

(1918) and by Perkins and Smith (1925) are important. The northern limit of the area studied by Katz is about 25 miles south of Lewiston (Fig. 2). He lists the following formations:

Carboniferous (Pennsylvanian?)
- Casco Bay group
  - Mackworth slates and quartzites
  - Jewell phyllite and slates
  - Spurwink limestone and phyllite
  - Eliot slates
    - Scarboro argillaceous gray and black phyllite
    - Diamond Island slates
    - Spring Point greenstone
    - Cape Elizabeth graywacke, phyllite, and slate
- Kittery quartzite and argillites

Pre-Cambrian(?)
- Berwick gneiss, highly crystallized and metamorphosed graywacke, quartzite, and thin micaceous beds
- Algonkian(?) complex of rhyolite flows, tuffs, slates, schists, and graywacke gneiss

Katz placed the Kittery conformably below the Casco Bay group and unconformably above the Berwick. He suggested that the Kittery is part of the Merrimack quartzite of Massachusetts.

Perkins and Smith mapped in the northern third of the Waterville, Vassalboro, Liberty, and Belfast quadrangles (Fig. 1). They described the following formations:

Middle Silurian
- Waterville shales; bluish calcareous shales and arenaceous shales; bluish quartzitic and pyritic shales with quartzitic lenses

Pre-Silurian
- transitional zone of sandstones interbedded with shales
- Vassalboro sandstone and associated quartzite, biotite schist, and phyllite
- Branch Pond quartzitic gneiss and staurolite schist
- Hogback quartz-mica schist
- Knox biotite granite gneiss

Cambrian
- Penobscot formation of schists, quartzites, and phyllites

Graptolites of the Waterville shales indicate mid-Silurian (Clinton or Lower Wenlock) age. These shales appear to be the equivalent of the Quoddy shales of the Eastport region (Bastin and Williams, 1912). Perkins and Smith seem to have established a sequence from the Waterville shales eastward across the strike to the Penobscot formation.

The significance of the work by Bastin, Katz, Perkins, and Smith is readily appreciated. A Cambrian age of some of the rocks of the Lewiston region has been suggested by Bastin; a mid-Silurian age for formations northeastward from Lewiston has been shown by Perkins and Smith; and a Carboniferous age for formations south and southeast of the area under discussion has been published by Katz.

The most recent geologic map of Maine, published in 1933, was prepared by Keith, assisted by Perkins and Charron. This map (Fig. 2)

incorporated the results of the papers cited, the work of uncited authors, and original field work by Keith. The belted outcrop of Paleozoic rocks ends abruptly between Augusta and Waterville. The major portion of Kennebec and all of Androscoggin, Oxford, Sagadahoc, and Lincoln counties is shown as pre-Cambrian with granitic intrusions.

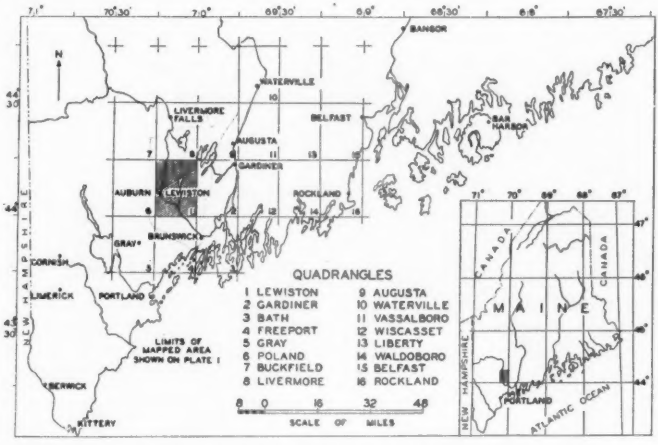

FIGURE 1.—*Location of the Lewiston region*

FIELD WORK

The writer spent the greater part of 7 summers mapping formations of the Lewiston quadrangle and carrying on detailed reconnaissance in those areas where it seemed possible to establish correlations with formations described by earlier writers.

The rocks may be grouped into three major divisions: (1) metamorphosed sedimentary rocks which are now lime-silicate gneisses, granulites, marbles, amphibolites, gneisses, and schists; (2) igneous rocks which include granite, granodiorite, gabbro, and syenite, and their aphanitic equivalents; and (3) rocks of the metamorphosed sediments that have been contaminated in varying degrees by igneous intrusions. The degree of metamorphism increases toward the larger intrusives, in general, from northeast to southwest.

Some of the difficulties encountered in mapping the region are cited briefly. Key beds are wanting because of contamination by intrusives. Swamps and glacial drift abound. Beds of marble crop out only locally and may represent definite formational members, erosional remnants, or lenses scattered through an argillaceous and arenaceous sedimentary

series. No fossils have been found. It is believed, however, that a stratigraphic sequence has been established and that the proposed correlation is valid.

ACKNOWLEDGMENTS

The writer wishes to thank those who have offered advice and counsel to him in this study. Edward H. Perkins, late of Colby College, and

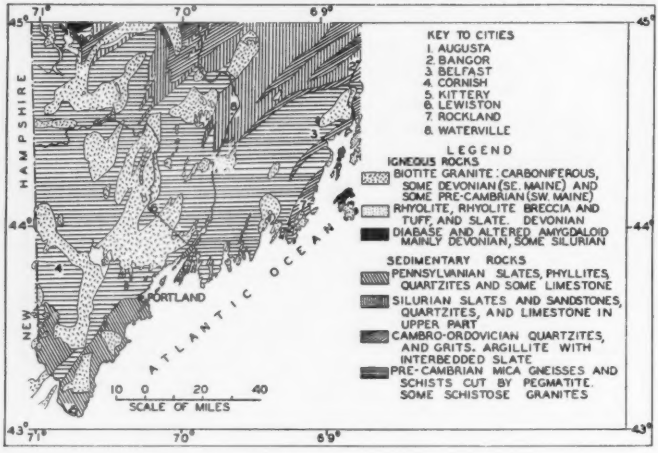

FIGURE 2.—*Geology of southwestern Maine*

Edward S. C. Smith, of Union College, conducted the writer to localities that they had described. Dr. Esper S. Larsen, of Harvard University, aided in the study of some of the thin sections made during the investigation and offered valuable advice. John B. Hanley mapped the adjacent Poland quadrangle and assisted in much of the field work of the western portion of the Lewiston quadrangle. The writer is especially indebted to Dr. Marland Billings, of Harvard University, for his counsel in the field, for pointing out that certain parallels exist in the metamorphism of the Littleton-Moosilauke area of New Hampshire and the Lewiston region of Maine, and for his assistance in the organization of the manuscript.

The writer expresses his thanks to the management of the Lawrence Portland Cement Company, at Thomaston, Maine, for the many chemical analyses made gratuitously by their chief chemist, Mr. J. G. Thompson, and to The Geological Society of America for a grant from the Penrose Bequest which made this study possible.

Age	Formation		Symbol	High-grade (kata) zone	Thickness (Feet)
SILURIAN	Clinton	SABATTUS	Ss	Quartz-muscovite schist Quartz-muscovite-sillimanite schist Quartz-biotite-garnet schist Quartz-biotite-sillimanite schist Quartz-mica-sillimanite schist Quartz-mica-graphite-sillimanite schist Quartz-garnet schist Quartz-feldspar-biotite schist Quartz-biotite schist Marble	3000
ORDOVICIAN (?)	ANDROSCOGGIN		Oa	Granulite Lime-silicate gneiss Quartz-feldspar-diopside gneiss Quartz-feldspar-biotite schist Garnet-diopside gneiss Marble	3500
CAMBRIAN	TAYLOR BROOK		Ct	Coarse-grained quartz-feldspar-biotite gneiss; probably highly injected Pejepscot	3500
	PEJEPSCOT		Cp	Quartz-feldspar-biotite gneiss Quartz-feldspar-biotite-hornblende gneiss Quartz-feldspar-biotite schist Migmatites Amphibolites	6000

TABLE 1.—*Lithology of formations*

zone	Thickness (Feet)	Formation	Symbol	Middle-grade (meso) zone	Formation
nite ist schist chist imanite hist	3000	WINTHROP	Swp	Quartz-mica chloritoid phyllite Quartz-mica-staurolite phyllite Quartz-mica-garnet-staurolite phyllite Metamorphosed limestone lenses and beds	WATERVILLE
gneiss chist	3500	Maintains same general characteristics as in high-grade zone Lime-silicate gneiss merges perceptibly into more arenaceous and argillaceous beds northeastward from type locality in the Lewiston region toward the Tacoma Lakes and Litchfield areas			VASSALBORO
ldspar- y highly	3500				
neiss orn- chist	6000	Maintains same general characteristics as in high-grade zone Garnetiferous gneisses and amphibolites become more prominent along eastern margin of the mapped area			BRANCH POND

rmation	Symbol	Low-grade (epi) zone
ERVILLE	Sw	Dark-blue calcareous shales interbedded with gray arenaceous shales Dark bluish slates interbedded with coarse quartzitic layers Limestones interbedded with shales Quartzites interbedded with phyllites
ALBORO	Sv(?)	Massive bluish-gray sandstone Calcareous mica phyllite Biotite phyllite Limestone Calcareous sandstone
CH POND	Cbp	(North and East of Gardiner and Augusta) (by Perkins and Smith) Bluish quartzitic and feldspathic gneiss Staurolite-bearing feldspathic schist (South and southeast of Gardiner) (by Fisher) (included in Pejepscot) Quartz-hornblende-garnet-biotite gneiss Epidote-hornblende-chlorite schist

PHYSIOGRAPHY

The Lewiston region is located in the Central Uplands of the New England section of the Appalachian Highlands, near the boundary with the Coastal division. Low glaciated hills rise from drift-filled depressions. No formation has distinctive topographic expression. The highest points in the Lewiston quadrangle, in general, are determined by structure.

The Androscoggin is the important river. Its course is not confined to any formation (Pl. 1) but is controlled, in part, by structure. The Little Androscoggin joins the Androscoggin River from the west. The Sabattus and Little rivers are the only other important streams. Both are tributary to the Androscoggin. The lakes of the quadrangle and vicinity present an interesting example of structural control.

DESCRIPTION OF FORMATIONS

GENERAL STATEMENT

Five distinct formations have been mapped in the Lewiston area (Table 1). These were formerly argillaceous, arenaceous, and calcareous sediments which are now in the high-grade zone of metamorphism (Pl. 1).

PEJEPSCOT FORMATION

General description.—The type locality of the Pejepscot formation is a road cut half a mile west of the village of Pejepscot (Pl. 1). Characteristic minerals indicate metamorphism in the high-grade zone.

Three phases have been differentiated: (1) quartz-feldspar-biotite gneiss, (2) quartz-biotite schist, and (3) amphibolite. The quartz-feldspar-biotite gneiss is coarse-grained. An analysis of an average specimen is given in Table 3, no. 4, and the mode in Table 2, nos. 1 and 4. Quartz makes up about 40 per cent of most specimens. Feldspar is polysynthetically twinned andesine (An_{40}), generally unaltered. Biotite ranges from nearly colorless through pale yellow to moderate yellowish brown. Alteration is to chlorite. Plates are usually oriented parallel to the foliation (Pl. 6, figs. 1, 2).

The quartz-biotite schist is fine-grained. An analysis is given under Table 3, no. 3, and the mode is in Table 2, no. 3. Although the bedding is thick, individual laminae of quartz and biotite are thin.

The amphibolite is represented in Table 3 by analysis no. 1; nos. 7, 14, and 15 are given for comparison. It contains 70 per cent of euhedral to subhedral, basic to pargasitic hornblende. Diopside makes up about 14 per cent. Uralitized augite encloses carbonate in thin lenses parallel to foliation. Feldspar is uncommon but in specimens rich in amphibole it is anorthite (An_{85}). Microcline is not abundant. Accessory minerals are

TABLE 2.—*Modes of rocks of the Pejepscot and Taylor Brook formations*

Rock name	1	2	3	4	5	6	7	8	9
No. of sections	3	2	3	1	2	2	1	2	2
Quartz	45	20	35	20		10	10	47	45
K-feldspar	7			10	4(m)			8	
Albite-Oligoclase		An_{12} 12	An_{14} 20					An_{11} 22	An_{10} 30
Oligoclase-andesine	An_{40} 15			An_{25} 30					
Labradorite-bytownite					An_{60} 15	An_{55} 8	An_{58} 35		
Muscovite			10					5	8
Biotite	30	35	25	35*	10		30	14	15
Hornblende		5	5		65	50	15		
Diopside		15							
Pyroxene						25	tr		
Garnet	tr		5	5					2
Calcite		tr	tr		2	tr	tr		
Sphene		tr			3	5	tr	2	
Zircon	tr								
Graphite	tr								

* largely chloritized; (m) chiefly microcline.

Explanation of Table 2.

1. Pejepscot gneiss from type locality (Pl. 1), same specimen used for anal. 4, Table 3.
2. Pyribole facies of Pejepscot gneiss, same locality as 1.
3. Schist facies of Pejepscot gneiss, from railroad cut north of Danville (Pl. 1). (*See* analysis 3, Table 3.)
4. Pejepscot gneiss, Rock Mill gorge, west end of pond 4 miles southwest of Durham (Pl. 1).
5. Amphibolite, type locality at Parson's Mill (Pl. 1). (*See* analysis 1, Table 3.)
6. Amphibolite from southeast shore of Taylor Pond (Pl. 1).
7. Hornblende facies of Pejepscot gneiss from bank of Little Androscoggin River in New Auburn.
8. Taylor Brook gneiss from Merrill Hill, Auburn, half a mile north of Parson's Mill.
9. Taylor Brook gneiss, Maine Central Railroad cut, at Taylor Brook (Pl. 1). (*See* analysis 6, Table 3).

biotite, calcite, sphene, pyrite, pyrrhotite, graphite, and quartz (Pl. 6, fig. 5).

Distribution.—A regional distribution of the Pejepscot between Robinson Mountain and Bunganuc Landing indicates a thickness of approximately 10,000 feet.

In the southeastern portion of the Lewiston quadrangle and in the western part of the Gardiner quadrangle pegmatite masses are injected into the gneiss.

The schist facies crops out in a railroad cut north of Danville (Pl. 1) where it is cut by pegmatite, granite, and basic dikes. Hanley has traced the schist northward to beyond Taylor Pond and Lake Auburn. In the southwest portion of the mapped area a thickness of 9000 feet is indicated. At Bunganuc Landing an epidote-chlorite-hornblende schist occurs at or near the top of the Pejepscot (Pl. 6, fig. 6).

The amphibolite crops out at Parson's Mill where it overlies conformably the Taylor Brook gneiss. Both rock types are cut by a basic dike and a schorl-bearing pegmatite.

The marked variation in mineral content of the amphibolite indicates that it might have been an impure limestone, a bedded basic tuff, or a basic sill. The writer prefers the first interpretation because hornblende forms large portions of some of the lime-silicate gneiss beds which overlie the amphibolite, and because similar amphibole-rich lenses or beds occur in the lime-silicate gneiss of the Androscoggin formation which has been proved to be an impure limestone.

Lack of continuous outcrops of this amphibolite and lack of indisputable evidence that other outcrops of amphibolite are at the same stratigraphic level make it difficult to determine whether these beds should be placed near the top of the Pejepscot formation or near the base of the Androscoggin formation.

TAYLOR BROOK FORMATION

General description.—The type locality of the Taylor Brook formation is in Taylor Brook in the western part of the city of Auburn. The Taylor Brook formation is a coarse-grained, quartz-feldspar-biotite gneiss (Pl. 6, fig. 4). Chemical analysis of a typical specimen is given in Table 3, no. 6; the mode is shown in Table 2, nos. 8 and 9. The quartz grains average 1 mm., are somewhat rounded, and show slight wavy extinction. A few finely granulated quartzite lenses occur. Albite-oligoclase is the most common feldspar. In general they are larger than the feldspars of the typical Pejepscot gneiss. The biotite ranges from pale dirty yellow to deep red brown. The ends are ragged, and about one-third of the biotite has been altered to muscovite due to the introduction of potash solutions. Accessory minerals are chlorite, zircon, and a few slightly chloritized garnets containing biotite and quartz in the fractures.

Distribution.—The Taylor Brook formation covers an area of approximately 10 square miles and has a thickness of 3500 feet. A quarter of a mile upstream from the City Rapids the Taylor Brook gneiss occurs in an

TABLE 3.—*Chemical analyses*

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
SiO_2	47.51	54.59	63.89	68.30	69.06	74.18	51.64	73.12	32.36	9.46	39.32	41.15	41.63	50.00	50.83
TiO_2	1.23	1.05	0.81	0.83	0.85	0.69	1.33	0.20	0.13	0.00	1.70	1.60	3.95	0.82	1.10
Al_2O_3	15.83	20.70	15.11	13.85	13.71	11.83	17.62	3.12	4.95	2.12	14.48	13.51	13.26	18.84	18.64
Fe_2O_3	1.00	0.93	0.68	0.47	0.31	0.22	1.14	0.34	0.00	0.00	2.01	2.32	3.09	2.57	2.84
FeO	7.97	6.44	5.31	4.45	5.24	3.78	7.80	1.68	0.71	0.15	8.73	8.63	9.92	5.51	5.97
CaO	12.94	2.00	2.81	3.35	1.50	1.10	6.44	11.44	31.16	39.54	8.30	8.75	8.86	10.65	7.50
MgO	8.86	4.42	3.88	3.16	2.64	1.56	7.74	3.90	3.55	9.16	11.11	10.09	7.31	4.63	4.90
Na_2O	1.70	3.28	2.33	2.08	2.87	2.44	4.52	0.22	0.68	0.00	3.76	3.21	2.49	4.46	4.22
K_2O	0.69	4.10	3.07	2.51	2.51	2.72	0.25	1.55	0.84	0.12	0.87	1.22	3.32	1.18	1.83
H_2O	1.15	1.82	1.24	0.77	0.92	1.17	1.29	0.40	0.13	0.08	2.57	3.05	1.35	1.00	1.40
$-H_2O$	0.06	0.14	0.05	0.02	0.06	0.07	n.r.	n.r.	n.r.	n.r.					
CO_2	0.50	n.d.	0.26	0.13	n.d.	0.18	0.00	3.95	25.88	39.54	5.25	5.54	n.d.	0.10	0.11
P_2O_5	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.09	0.00	0.00	0.00	n.r.	n.r.	n.r.	n.d.	n.d.
BaO	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.00	n.d.	n.d.	n.d.	n.r.	n.r.	n.r.	n.d.	n.d.
ZrO_2	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.00	n.d.	n.d.	n.d.	n.r.	n.r.	n.r.	n.d.	n.d.
Total	99.44	99.47	99.44	99.92	99.67	99.94	99.86[a]	99.92[b]	100.42	100.17	98.10	99.07	95.18	99.76[c]	99.34[d]
Sp. Gr.	3.081	2.670	2.747	2.761	2.723	2.692	2.901	2.759	2.760	2.755	n.r.	n.r.	n.r.	n.r.	n.r.

a = MnO–0.12; S–tr.
b = S–0.04
c = MnO–0.08; Cl–0.10; S–0.03
d = MnO–0.10; Cl–0.03; S–0.01
n.d. = not determined
n.r. = not reported

Analyses by L. C. Armstrong, University of Minnesota. Numbers refer to Bates College collection numbers.

1. Amphibolite of Pejepscot gneiss; Parson's Mill outcrop on Mechanic Falls road at Taylor Brook in Auburn; 71111.
2. Sabattus schist from Sabattus Mountain, Lewiston quadrangle, 4177.1.
3. Schist facies of Pejepscot gneiss formation; type locality 100 yards north of Danville railroad station on Maine Central Railroad.
4. Pejepscot gneiss; artificial road-side outcrop at Pejepscot; Freeport quadrangle.
5. Highly injected basal beds of Lewiston City quarry.
6. Taylor Brook gneiss; Maine Central Railroad cut south of Taylor Brook in Auburn.

Analyses 7, 8, 9, and 10 are from Table 19, (Billings, 1937, p. 556). They are analyses 11, 4, 2, and 3 respectively.

7. Fine-grained amphibolite; volcanic member of Littleton formation.
8. Diopside-actinolite granulite; middle-grade Fitch formation.
9. Arenaceous dolomitic limestone; low-grade Fitch formation.
10. Arenaceous dolomitic limestone; low-grade Fitch formation. Analyses 11, 12, and 13 are from Merrill (1892, p. 54).
11. Camptonite; New Hampshire; dike 1. Hawes.
12. Dike 6, Lewiston City quarry.
13. Dike in Maine Central Railroad cut south of Auburn. Analyses 14 and 15 are from Adams and Barlow (1910, p. 104).
14. Analysis 2, typical specimen of amphibolite which alternates with thin beds of limestone; Maxwell's Crossing.
15. Analysis 3, typical harder amphibolite included in granite.

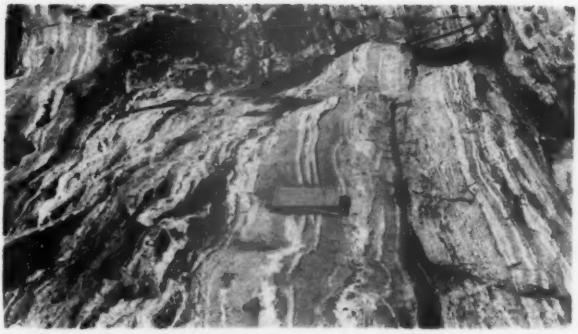

FIGURE 1. HARD SILICEOUS BEDS IN LIME-SILICATE GNEISS
Downstream side of Gulf Island Dam (Pl. 1).

FIGURE 2. OVERTURNED WEST LIMB OF ANTICLINAL FOLD

FIGURE 3. EIGHT-FOOT PEGMATITE SILL FORMING TOP OF CITY RAPIDS

LIME-SILICATE GNEISS OF THE ANDROSCOGGIN FORMATION

15. Analysis 3, typical harder amphibolite included in granite.

are analyses 11, 4, 2, and 3 respectively.

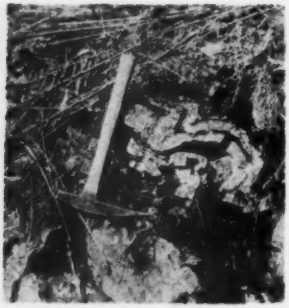

FIGURE 1. PITCHING MINOR FOLD ON SOUTHEAST SLOPE OF ROBINSON MOUNTAIN North of South Lewiston (Pl. 1).

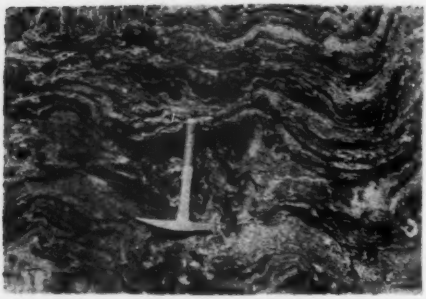

FIGURE 2. FOLDS IN MARBLE ON SOUTH SLOPE OF MONMOUTH RIDGE North of East Wales (Pl. 1).

FIGURE 3. CRENULATIONS IN MARBLE IN LEWISTON CITY QUARRY Width of outcrop, 8 feet.

FOLDS AND CRENULATIONS IN MARBLE

abandoned quarry on the nose of a plunging anticline. One hundred yards farther upstream quartz-biotite schist, closely resembling schist of the Androscoggin formation, is associated with thin bands of amphibolite. Quartz-biotite gneiss overlies biotite schist and is well exposed on both sides of the river upstream from Lewiston. Beds of marble overlie the quartz-biotite gneiss.

From Deer Rips Dam to Gulf Island Dam (Pl. 1) outcrops of Taylor Brook gneiss, lime-silicate gneiss, and marble of the Androscoggin formation alternate due to plunging structures. At Deer Rips Dam a garnetiferous facies of the Taylor Brook gneiss strikes north-south and dips steeply to the east.

CONTACT OF TAYLOR BROOK AND ANDROSCOGGIN FORMATIONS

The contact between the basal beds of the Androscoggin formation and the underlying Taylor Brook gneiss was exposed at the west abutment of Gulf Island Dam by flood waters in March 1936. Marble beds of the Androscoggin formation crop out 200 yards west of Deer Rips Dam and are involved in small synclinal folds with the Taylor Brook formation. Local dips and strikes of the Taylor Brook and Androscoggin formations at or near the contact are essentially the same. The Androscoggin formation overlies conformably the Taylor Brook gneiss.

ANDROSCOGGIN FORMATION

General statement.—The type locality of the Androscoggin formation is at the City Rapids between Lewiston and Auburn (Pl. 2, fig. 3). Characteristic minerals indicate metamorphism in the high-grade zone.

Four phases have been identified: (1) highly injected biotite-garnet gneiss, (2) lime-silicate gneiss, (3) marble, and (4) quartz-biotite schist.

Biotite-garnet gneiss.—Highly injected coarse-grained biotite-garnet gneiss crops out in several places in contact with lime-silicate gneiss of the Androscoggin formation. These injected gneisses in some places resemble the Taylor Brook gneiss and are regarded as transitional beds in or near the base of the Androscoggin formation.

A highly injected quartz-feldspar-garnet gneiss forms the basal portion of the working face of the Lewiston City quarry (Pl. 1). The gneiss contains large feldspars, sporadic 1-inch garnets, and visible graphite (Pl. 9, fig. 2). There are lit-par-lit injections of quartz. Gradation from gneiss into biotite-muscovite schist, along the strike and upward into the lime-silicate gneiss and marble, is observed. The lithologic similarity of the calcareous beds of the Androscoggin formation at this place, and of the lime-silicate gneiss in the upper portions of the Taylor Brook forma-

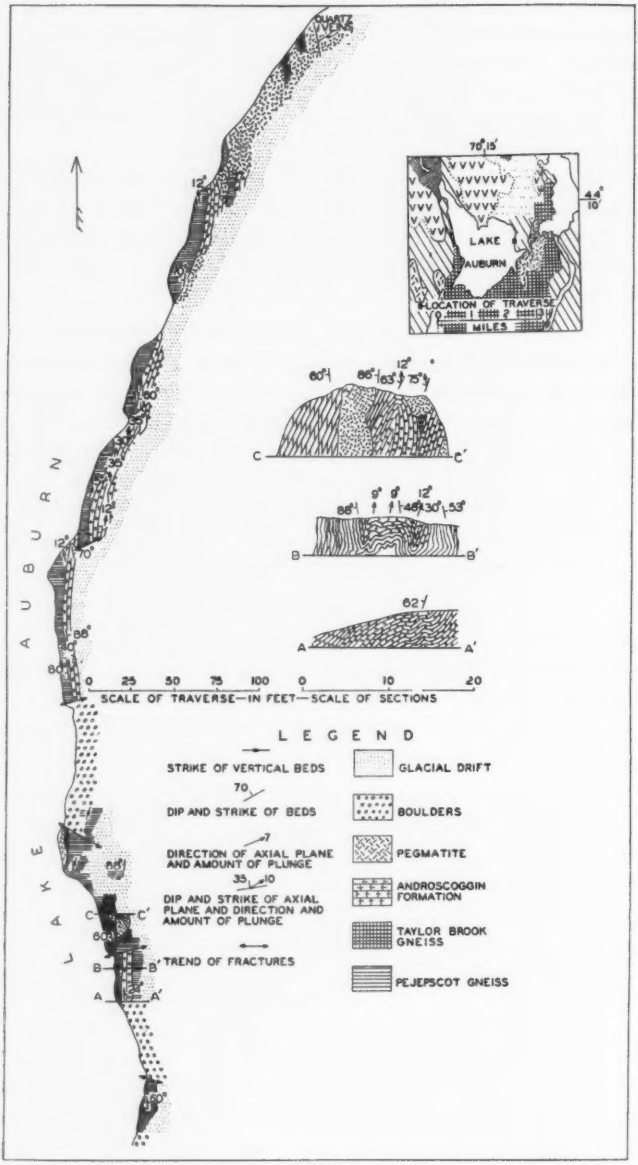

FIGURE 3.—*Pace and compass traverse along east shore of Lake Auburn*

tion, suggests that the biotite-garnet gneisses are facies of the underlying and overlying formations (*See* Table 3, analysis 5).

One mile east of the City quarry, 12 feet of marble crops out conformably above 8 feet of the transitional beds. Half a mile northeast lime-silicate gneisses are exposed above the transitional beds. In these two localities the associated rock type and lithologic characteristics suggest either basal Androscoggin formation or beds transitional between this formation and the underlying Pejepscot formation.

The lime-silicate gneiss of the Androscoggin formation is interbedded and infolded with a coarse-grained feldspathic gneiss along the eastern shore of Lake Auburn (Fig. 3). The Taylor Brook gneiss in this locality is identified by its massive character, the presence of large quartz veins, and the well-developed feldspar crystals. The transitional beds here appear to belong to the Taylor Brook formation.

Marble.—The type locality of the marble of the Androscoggin formation is the Lewiston City quarry (Pl. 1). The marble is exposed in a working face 300 feet long and 60 feet high and is cut by at least 19 basic dikes which are from 14 inches to 15 feet thick, and by some simple and complex pegmatites (Fig. 10, k). The marble is massive and rests conformably on the previously described transitional beds. There are numerous small folds overturned and recumbent to the northwest (Pl. 3, fig. 3). Folds plunge about 20° NE. No faults have been observed.

Light reddish-brown mica ranges up to nearly 50 per cent in some of the marble beds. Interbedded granulites are composed of feldspar, garnet, clinozoisite, biotite, and scattered calcite (Fisher, 1936) (Pl. 9, fig. 1). Thin sections of highly silicated marble show quartz grains with wavy extinction in two distinct zones. Graphite is common in the zone of crushed quartz. Calcic feldspars show slight amounts of sericite. Chlorite is common along the borders of the quartz grains. Zircon, included in the chlorite, indicates chloritization of biotite by invading pegmatites.

Scattered tourmaline, abundant vesuvianite, graphite, and pyrrhotite are found in the marble at or near the contacts with the basic dikes. Zones of biotite, succeeded with distance from the contact by zones of quartz, clinozoisite, and anorthitic feldspar, are common.

Calcite-rich portions of some slides carry metacrysts of diopside, needles of actinolite, and shreds of graphite. They are sharply separated from beds rich in clinozoisite. Diopside and hornblende are more common at a distance from the dike contacts. Common accessory minerals of the marble are vesuvianite, scapolite, zircon, and sphene (Pl. 7, figs. 3, 4).

Chemical analyses of the marble of the Lewiston City quarry are shown in Table 4, analyses, 1, 3, 4, 5, 7, 8, 10, 11, and 12, and the mode is given in Table 5, nos. 1 and 7.

The development of scapolite and the chloritization of biotite and hornblende is strongest where juices of the invading pegmatites have been most active. Actinolite, replaced by chlorite, diopside, common hornblende, and clinozoisite are associated with calcite and graphite in marble beds near the pegmatites (Fisher, 1934).

Calcite-rich beds, small-scale folding, and basic dikes are not so abundant in the Martin quarry, a mile southeast of the Lewiston City quarry, although general structural and lithologic features are essentially the same in the two quarries.

The marble beds of Robinson Mountain, east of Lewiston (Pl. 1), occur in a tightly appressed anticline slightly overturned to the west and plunging to the northeast (Pl. 3, fig. 1). Crystals of vesuvianite 1 to 8 inches in length, smaller brown garnets, minor amounts of apatite and fluorite, diopside, and calcite are found here. (*See* Table 5, mode no. 5, and Table 4, analysis 13.) Vesuvianite and fluorite, associated with brown garnet, are not found in the marble outcrops elsewhere in the area. The general lithology of the marble, types of rocks involved, general structures, and contact mineralization are essentially the same in the Robinson Mountain locality as they are in the grossularite-vesuvianite locality between Cornish and Limerick (Fig. 1).

Contacts between the marble beds and the transitional beds are conformable in the Lewiston City quarry and at Dill Hill. The most southeasterly occurrence of marble is along the Androscoggin River at Lisbon Falls, where it lies conformably above the Pejepscot gneiss. The general distribution of the marble suggests lenticular structure or the remnants of a once continuous bed that has been pulled apart.

An original argillaceous, perhaps slightly arenaceous, low-magnesium limestone is indicated by the suite of high-grade zonal minerals. Shale, alternating with pure limestone, is indicated by biotite schist interbedded with almost pure marble. Diopside-pyribole-feldspar beds in the marble indicate a close relationship between the Taylor Brook and the Pejepscot gneisses, and a closer genetic relationship between the lime-silicate gneisses of the Androscoggin formation.

Lime-silicate gneiss.—The best section for study of the lime-silicate gneiss of the Androscoggin formation is at the City Rapids in the Androscoggin River. The river flows across the strike of the gneiss (Pl. 2, fig. 3). The gneiss is injected by pegmatites, aplites, and basic dikes at the City Rapids, Deer Rips Dam, and Gulf Island Dam.

TABLE 4.—*Chemical analys*

	1	2	3	4	5	6	7	8
SiO_2	6.54	10.94	12.20	13.26	14.78	19.68	19.86	21.
Al_2O_3	3.97	3.63	1.95	3.00	4.60	8.16	6.66	4.
Fe_2O_3	2.73	2.15	1.95	1.76	2.64	4.20	3.12	3.
CaO	47.91	45.81	47.49	45.61	44.98	35.98	38.91	40.
MgO	1.95	2.40	2.31	2.25	2.43	4.25	3.93	3.
Ignition loss	36.77	34.39	34.79	34.50	31.12	25.98	26.73	26.
Total	99.87	99.32	100.69	100.38	100.55	98.25	99.21	100.
Vol. CaO	47.13	44.10	44.78	44.17	39.34	32.34	34.25	33.
Sp. Gr.	2.799	See #9	2.785	2.772	2.763	See #9	2.826	2.

	16	17	18	19	20	21	22	23
SiO_2	48.08	49.24	49.32	49.56	50.00	50.24	51.24	52.
Al_2O_3	15.60	14.85	16.46	12.28	18.11	23.48	13.79	17.
Fe_2O_3	8.00	8.39	7.22	5.08	7.81	5.72	6.05	6.
CaO	19.25	15.90	17.57	20.50	8.79	9.20	14.23	17.
MgO	6.06	7.12	6.16	3.71	6.88	4.76	4.80	5.
Ignition loss	1.07	3.53	0.53	6.08	2.75	1.43	7.27	0.
Total	98.06	99.03	97.26	97.21	94.34	94.83	97.38	100.
Vol. CaO	1.23	5.27	1.68	7.74	2.24	1.79	8.75	3.
Sp. Gr.	2.812	2.871	2.743	2.795	2.753	2.834	2.751	2.

Nos. 1 to 30 inclusive, by J. G. Thompson, Chief Chemist, Lawrence Portland Cement Company, Thomaston, Maine.

Mr. Thompson states that "Volumetric CaO figures refer to the volumetric acid alkali determination of the calcium carbonate or its equivalent in the samples, computed to and expressed as an oxide. The disparity in the volumetric determined figures as shown, and the total as shown in the gravimetric analyses, is merely an indication of the amount of lime or equivalent that is tied up in minerals in the rock samples other than as carbonates."

(Numbers after specimen refer to Bates College collection numbers.)

1. Marble, Androscoggin formation; random sample from west portion of Lewiston City quarry; biotite-rich portion; 68817.

2. Marble, south side of Sabattus-Gardiner highway, half a mile east of South Monmouth; calcite-biotite zone.

3. Marble, Androscoggin formation; directly beneath graphite-bearing pegmatite lens, Lewiston City quarry; 6885.

4. Marble, Androscoggin formation; 4 feet from basic dike contact number 4, Lewiston City quarry, 17 and Me. 276.

5. Marble, Androscoggin formation; random sample; west portion of City quarry; diopside-rich bed; 68817.

6. Same locality as 2 above but somewhat weathered.

7. Uppermost bed of marble, Androscoggin formation; Lewiston City quarry; 6881, Me. 8.

8. Same bed as 5 above; calcite-rich portion.

9. Same locality as 2 above; biotite-rich portion.

10. Marble, Androscoggin formation; lowermost beds of working face of Lewiston City quarry; 68812.

11. Marble, Androscoggin formation; middle portion of working face of Lewiston City quarry; 6886.

12. Marble, Androscoggin formation; contact with basic dike number 4, Lewiston City quarry; 17. Compare with analysis 4 above.

13. Marble, Androscoggin formation; Robinson Mountain, Lewiston quadrangle; 826, Me. 275.

14. Lime-s
5679, Me. 17

15. Lime-s
Androscoggi

16. Lime-s
B.M.415, Le

17. Lime-s
Pond road,

18. Diopsid

19. Lime-s
and Pejepsc

20. Lime-s
of Bald Hill

21. Greenis
Auburn reser

22. Lime-s

23. Grayish
River Road,

24. Greenis
3211.

25. Sandy,

26. Iron st

27. Lime-s
College Road

28. Finely
quadrangle.
cally with B

29. Finely
Berwick gneis

30. Lime-s
6319.

emical analyses

7	8	9	10	11	12	13	14	15
19.86	21.14	27.48	27.60	31.88	43.24	43.44	45.80	47.16
6.66	4.93	10.06	9.94	9.09	14.19	11.57	20.96	18.02
3.12	3.71	4.78	3.90	5.47	4.29	6.83	8.20	5.86
38.91	40.79	28.45	35.56	32.22	21.76	21.13	20.50	17.36
3.93	3.05	6.69	3.78	4.64	5.36	7.82	4.96	5.66
26.73	26.39	18.83	19.14	16.45	9.44	7.10	1.11	2.58
99.21	100.01	96.29	99.92	99.75	98.28	97.89	101.53	96.64
34.25	33.74	25.24	24.68	20.98	11.22	7.62	3.59	4.48
2.826	2.883	2.739	2.895	2.793	2.862	2.82	2.946	2.749

22	23	24	25	26	27	28	29	30
51.24	52.48	54.00	54.40	57.60	58.64	63.48	63.68	66.44
13.79	17.91	17.91	12.25	20.76	13.63	12.93	11.88	11.97
6.05	6.25	4.49	6.83	6.44	6.05	5.47	4.68	5.47
14.23	17.57	17.57	16.74	5.86	12.13	9.00	7.11	11.09
4.80	5.16	3.82	4.56	3.23	5.18	4.76	3.42	4.08
7.27	0.76	0.40	4.25	1.97	0.57	1.22	6.03	0.56
97.38	100.13	98.19	99.03	95.86	96.20	96.86	96.80	99.61
8.75	3.76	3.64	5.44	3.59	1.47	0.44	8.18	0.61
2.751	2.92	2.809	2.798	2.757	2.823	2.77	2.75	2.703

14. Lime-silicate gneiss, Androscoggin formation; one mile northeast of Highland Spring; 5679, Me. 174 and 269.

15. Lime-silicate gneiss, with lit-par-lit quartz; west abutment of Deer Rips Dam, Androscoggin River; 6524, Me. 16.

16. Lime-silicate gneiss; weathered; half a mile north of B.M.409 on road leading to B.M.415, Lewiston quadrangle, 2691, Me. 270.

17. Lime-silicate gneiss; 0.9 miles southeast of Greene, south side of Greene-Sabattus Pond road, 68999.

18. Diopsidic top portion of specimen reported in 16 above.

19. Lime-silicate gneiss; transitional beds between marble of Androscoggin formation and Pejepscot gneiss; Applesass Hill, Lewiston; 6977, Me. 171 and 179.

20. Lime-silicate gneiss; south-central rectangle, Poland quadrangle; one mile northwest of Bald Hill, Me. 277.

21. Greenish-gray lime-silicate gneiss and interbedded biotite schist; Merrill Hill, near Auburn reservoir, 676.

22. Lime-silicate gneiss from Little Androscoggin River, New Auburn; 6792.

23. Grayish green quartzose facies of lime-silicate gneiss; south of B.M.121, on South River Road, Auburn; 7283, Me. 87 and 278.

24. Greenish gray lime-silicate gneiss from northeastern portion of Lewiston quadrangle; 3211.

25. Sandy, biotitic schist; Sabattus formation, near Deer Rips dam; 6521, Me. 303.

26. Iron stained Taylor Brook gneiss; 6791.

27. Lime-silicate gneiss, abundant diopside and large calcite plates; Stetson Brook near College Road School, Lewiston quadrangle; 6452.

28. Finely banded, purplish-gray, calcareous schist; near Stickney's Corner, Liberty quadrangle. (Belongs in Branch Pond terrain of Perkins and Smith.) Identical lithologically with Berwick gneiss from Stevens Avenue quarry, Portland.

29. Finely banded purplish-gray schist, Liberty Quadrangle. (Resembles interbeds of Berwick gneiss, Stevens Avenue Quarry, Portland.)

30. Lime-silicate gneiss; Augusta-Lewiston highway near Lewiston-Greene town line; 6319.

A measured section at City Rapids showed the following:

Feet	Inches	
25		lime-silicate gneiss and subordinate biotite schist
5		basic dike, N. 75° E., and 70° NW.
5		lime-silicate gneiss
22		cross-cutting pegmatite
27		interbedded gneisses, schists, and marble
2		concordant tourmaline-bearing aplite
27		interbedded injection gneiss and marble
8		marble, N. 41° W., and 32° NE.
3	6	cross-cutting pegmatite
12		quartz-feldspar-biotite gneiss
10	4	lime-silicate gneiss with some biotite schist
24		interbedded lime-silicate gneiss, with quartz-feldspar-biotite gneiss, and marble
15	9	lime-silicate gneiss with 2-inch hornblende crystals along fracture planes
4		garnetiferous biotite schist
10		quartz-biotite gneiss injected by pegmatite
15	4	lime-silicate gneiss
20		covered by water from spillway
8	6	marble and interbedded thin beds of biotite schist
10		lime-silicate gneiss, N. 34° W., 20° NE.
3	6	quartz-feldspar-biotite gneiss, N. 58° W., 22° NE.
14		lime-silicate gneiss
	6	concordant pegmatite
6		garnet-biotite gneiss
3	9	interbedded lime-silicate gneiss and fine-grained quartz-feldspar-biotite gneiss
3		concordant pegmatite
10		lime-silicate gneiss
9		rusty pyritiferous graphitic schist
2	2	thinly banded garnetiferous injection gneiss, N. 3° E., 30° SE.
Total 306	4	

Approximately 109 feet is lime-silicate gneiss, 16 feet is marble, and 78 feet represents interbedded lime-silicate gneiss and schist. The remaining thickness consists chiefly of gneisses and schists of the Androscoggin formation.

The lime-silicate gneiss of the Androscoggin formation crops out in many places (Pl. 1):

(1) An abandoned quarry on Merrill Hill in Auburn exposes thin beds of marble, interbedded with lime-silicate gneiss and cut by a complex pegmatite and several basic dikes. Amphibolite occurs near the base of the beds.

(2) Along the eastern shore line of Lake Auburn (Fig. 3) and in low hills between the lake and the Androscoggin River, typical lime-silicate gneiss crops out.

(3) On Applesass Hill tightly folded lime-silicate gneiss is cut by quartz veins, pegmatite, granite gneiss, and basic dikes (Fig. 4; Fig. 10, H).

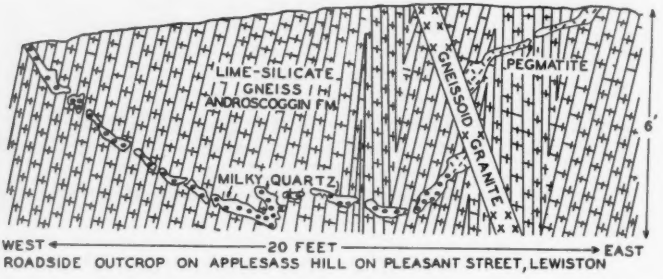

FIGURE 4.—*Roadside outcrop on Applesass Hill on Pleasant street, Lewiston*

(4) In the southeastern part of Lewiston lime-silicate gneiss crops out in appressed and slightly overturned folds (Pl. 2, fig. 2). This area is important, for here the lime-silicate gneiss of the Androscoggin formation is in conformable contact with sillimanite schist of the Sabattus formation.

(5) Norris (or Highmoor) Hill (Pl. 1) is composed of extremely weathered lime-silicate gneiss. The total thickness of the exposed beds is 50 feet. Many are rich in calcite. Quartz-muscovite schist of the Sabattus formation crops out on the northern and western slopes of the hill. Small, minor folds, on a northeasterly plunging anticline, are responsible for the occurrence of the lime-silicate gneiss in this area.

(6) In the southern part of the village of Greene (Pl. 1) is a 4-foot bed of massive, vitreous, silicated marble. It lacks the visible diopside and calcite crystals of the typical marble of the Androscoggin formation but shows marked effervescence. A chemical analysis is given in Table 4, analysis 17. The mode is shown in Table 5, no. 6.

Petrography of the lime-silicate gneiss.—The mode of a typical thin section is given in Table 5, nos. 8 and 9. Reddish-brown biotite, accompanied by fairly large amounts of andesine-labradorite, is prominent in some sections. Polysynthetically twinned feldspars (80 per cent anorthite) are common in sections rich in feldspars. Specimens rich in calcic feldspars are higher in calcite and chlorite content.

TABLE 5.—*Modes of rocks from Androscoggin formation*

Rock name	1*	2*	3	4	5	6	7*	8	9	10
No. of sections	7	3	2	4	2	2	2	3	1	2
Quartz	3			10	25	40	20	10	20	30
Calcite	80	65	45	8	15	3	20	8	3	
Garnet					5	5			10	20
Vesuvianite	tr				15		15			
Epidote										
Clinozoisite				5		20		10		
Scapolite					tr		2			
Sphene	tr			2	tr			3	tr	
Graphite	tr		tr		tr				tr	
Diopside	6	13		40	10	20	15	30	5	
Pyroxene										15
Hornblende								10		
Actinolite			10							
K-feldspar									10	
Albite-oligoclase										
Oligoclase-andesine										
Andesine-labradorite				An_{37} 25		An_{60} 10	An_{60} 10		An_{60} 20	An_{60} 35
Labradorite-bytownite					An_{72} 25			An_{80} 15		
Anorthite										
Muscovite										
Biotite	8	20	40	10		5	15	20	15	
Chlorite						7				

* Pyrrhotite a common accessory.

1. Marble of Androscoggin formation, Lewiston City quarry. (*See* analyses 1, 3, and 4, Table 4.)

2. Marble of Androscoggin formation from area half a mile east of South Monmouth (Pl. 1). (*See* analyses 2, 6, and 9, Table 4.)

3. Biotite-rich facies of No. 2. (*See* analysis 9, Table 4.)

4. Sections from beds underlying marble and overlying quartz-feldspar-biotite-gneiss in City quarry, Lewiston. (*See* analysis 35, Table 4.)

5. Vesuvianite-bearing marble from Robinson Mountain, half a mile north of South Lewiston (Pl. 1). (*See* analysis 30, Table 4.)

6. Marble, half a mile east of Greene, on Greene-Sabattus Pond road (Pl. 1). (*See* analysis 17, Table 4.)

7. Marble from contact with basic dike in Lewiston City quarry, Lewiston. (*See* analysis 12, Table 4.)

8. Typical lime-silicate gneiss of Androscoggin formation, from beds at west abutment of Deer Rips Dam. (*See* analysis 15, Table 4.)

9. Lime-silicate gneiss from old Franklin quarry, east slope of Merrill Hill, one mile northwest of junction of Little Androscoggin and Androscoggin rivers (Pl. 1). (*See* analysis 21, Table 4.)

10. Quartz-feldspar-garnet-diopside rock that occurs as discontinuous lenses or beds in aluminous beds of Androscoggin and Sabattus formations, 3½ miles northwest of Deer Rips dam.

Facies gradational between the lime-silicate gneiss of the Androscoggin formation and quartz-biotite gneiss of the same formation show a sharp line of separation between the lime-silicate portions of the rock and the quartz-biotite gneiss (Table 4, anal. 19).

Diopside predominates over common hornblende in the lime-silicate gneiss and is accompanied by polysynthetically twinned andesine-labradorite, quartz, biotite, magnetite derived from biotite, and scattered sphene (Pl. 9, fig. 2). Albite-oligoclase feldspar and slightly elongated but unstrained quartz grains form the groundmass of the quartz-biotite gneiss. Pargasitic hornblende is present in small amounts. There is no diopside. Biotite decreases with distance from the contact with the lime-silicate gneiss. In some of the quartz-biotite gneisses, scattered euhedral to subhedral grains of schorl occur.

Two distinct generations of quartz occur in the silicated marble in the Androscoggin formation at Greene village (Pl. 1). Smooth, mutual boundaries characterize the larger grains of quartz, but the smaller grains have sutured and interlocking boundaries. None of the quartz shows fracturing or wavy extinction. Chlorite replaces biotite along edges and cleavages. Biotite shows feathery edges against quartz. This silicated marble is bluish-green and somewhat similar in color to the limy beds of the Vassalboro formation. (*See* Table 4, anal. 17, and Table 5, no. 6.)

Northeastward continuation of Androscoggin formation.—Argillaceous and arenaceous sediments predominate in the Androscoggin formation half a mile northwest of Tacoma Lakes (Pl. 1; Pl. 4, figs. 1, 3). Here the formation consists of quartz-biotite schists, fissile and greatly weathered quartz-feldspar-biotite schists (Pl. 9, fig. 3), thin quartzites, and lime-silicate gneiss. The schists are finer-grained than in other areas. Actinolite in the Androscoggin formation is more abundant here than elsewhere. The quartz-biotite facies of the formation has been traced into the Vassalboro formation between Litchfield and South Litchfield.

The arenaceous facies of the Androscoggin is exposed along the south slope of Oak Hill (Fig. 5), 2½ miles east of Sabattus and a quarter of a mile south of cross section line BB′. The lime-silicate gneiss of the Androscoggin formation merges northeastward along the strike into subordinate lime-silicate gneiss and dominant quartz-biotite schist of the Tacoma Lakes area and indicates a change in original sedimentation.

VASSALBORO FORMATION

The Vassalboro formation is typically a massive, bluish-gray sandstone (Perkins and Smith, 1925, p. 223). Locally it is a quartzite; shaly layers have been altered to pyritiferous mica schists whose weathered surfaces are rusty.

Thin sections from the old Winslow tin mine (Pl. 1) south of Waterville reveal two phases: (1) a quartz-biotite phyllite, and (2) a quartz-biotite-calcite phyllite. The former contains small amounts of graphite

FIGURE 1. QUARTZ-BIOTITE SCHISTS, GRANULITE, THIN QUARTZITES, AND QUARTZ VEINS
In Androscoggin formation near Tacoma Lakes (Pl. 1). Picture area is 2 feet.

FIGURE 2. SABATTUS SCHIST; LIGHT AND DARK INTERBEDS
In flat exposure on Sabattus Mountain.

FIGURE 3. QUARTZ VEINS IN SAME OUTCROP AS FIGURE 1

QUARTZ-BIOTITE FACIES OF ANDROSCOGGIN AND SABATTUS FORMATIONS

FIGURE 1. SABATTUS MOUNTAIN, ACROSS SABATTUS LAKE
Type locality of formation. Northeasterly plunging beds of Androscoggin formation at center of far shore at light-colored spot.

FIGURE 2. SYNCLINAL ROLL IN SABATTUS FORMATION NEAR LEWISTON
Sabattus formation on left and Androscoggin formation on right. (Width of outcrop 18 feet).

FIGURE 3. CRENULATIONS IN SABATTUS FORMATION
Half a mile west of Figure 2. Strike of hammer is N. 39° W.

and sphene. The biotite developed from chlorite and is optically the same as that in the low- to middle-grade zone of the Waterville formation near Sidney Bog. Quartz grains range from 0.05 to 0.25 mm. The quartz-biotite-calcite phyllite contains about 20 per cent of calcite and is the more prominent member of the formation. Pyrite, chloritoid, and limonite are the chief accessories of the calcareous phase of the formation.

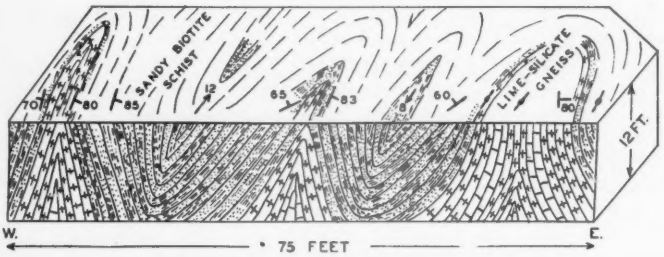

FIGURE 5.—*Structure of Androscoggin formation on Oak Hill*

SABATTUS FORMATION

General statement.—The Sabattus formation takes its name from excellent outcrops near or on Sabattus Mountain (Pl. 1). The "mountain" (Pl. 5, fig. 1) is 802 feet in elevation and 560 feet above Sabattus Lake. The general structure of the mountain (cross section BB′) is a closely folded syncline that plunges northeasterly and is slightly overturned to the northwest.

Several types of rock (all predominantly argillaceous) are mapped in certain local areas (Table 6, nos. 2-5), but none except the quartz-muscovite-sillimanite schist ("rusty schist"), which crops out on the mountain (Table 6, no. 2), is traceable for any considerable distance.

Distribution.—The Sabattus formation occupies the central portion of a syncline which extends northeasterly from Lewiston through Winthrop to Waterville (Pl. 1). Northeastward from Sabattus mountain the formation can be traced with ease through the finger lake country of Anabessacook, Maranacook, and Cobbosseecontee lakes. The long axes of these lakes are roughly parallel to the regional strike of the formation.

Several low rounded knobs of vertically dipping biotite-garnet-sillimanite schist occur in the sand plain east of Sabattus Mountain. Interbedded quartz-biotite-sillimanite schist and quartz-biotite schist crop out at East Wales (Pl. 1) along the Sabattus-Gardiner Highway (State Highway 126). The local strike is N. 40° E., with dips vertical to steep northeast.

A measured section at East Wales is as follows:

	Feet	Inches	
Top:			Sabattus formation
	3		quartz-biotite-sillimanite schist
	6		quartz-biotite schist
	1		quartz-biotite-sillimanite schist
	5	6	interbedded schists
	3		fissile, slabby, quartz-biotite schist
	42		quartz-sillimanite schist, quartzite, and quartz-biotite schist
	69		sandy quartz-biotite schist
	15		quartz-biotite schist with garnet and sillimanite
	15		pegmatite with large schorl crystals
	45		quartz-biotite schist, thin quartzite, and quartz-biotite-sillimanite schist
	6		quartz-biotite-sillimanite schist
	108		greatly weathered biotite schist
	48		interbedded biotite schist and thin quartzite
	4		garnetiferous quartz-biotite schist
			Androscoggin formation
	14		lime-silicate gneiss rich in diopside, and interbedded with quartz-biotite schist
	10	6	biotite schist cut by diopside-bearing quartz veins
	4	2	lime-silicate gneiss
	39		fissile, quartz-biotite schist which breaks into one-eighth inch slabs
	2	4	marble
	4		lime-silicate gneiss
Total	454	6	

The late Edward H. Perkins visited this outcrop with the writer and stated that the rock is similar to the Vassalboro formation.

East of Monmouth several anticlinal rolls bring beds of the Androscoggin formation into position and break the Sabattus into parallel belt. (*See* structure sections, Plate 1.)

On Minwah Hill, half a mile west of East Wales (Pl. 1), a vertically dipping, southwestward-facing cliff 70 feet high is cut by fractures parallel to the regional strike and dip of the rocks. Solution of interbedded calcareous zones in the quartz-mica-sillimanite schist has taken place. Some fractures are open for 2 feet in width and 12 feet along the strike. Red garnets associated with vein quartz, one-half inch diopside crystals, and calcite plates line the walls of some of the fractures. Sillimanite crystals, an inch in length, are numerous in some of the schist beds.

Quartz-mica-sillimanite schist crops out on the western flank of Sabattus Mountain. Lenses of quartz-feldspar-garnet-diopside are abundant.

TABLE 6.—*Modes of rocks from Sabattus and Winthrop formations*

Rock name	1	2	3	4	5	6	7	8	9	10	11
No. of sections	3	2	2	2	1	2	3	3	5	2	4
Quartz	27	80	45	35	65	55	40	30	40	55	47
Staurolite											5
Sillimanite	3		5		tr.		10 (k)	tr	tr	5	
Chloritoid								(lm)			4
Biotite	25		50	12	15		5	35	12	15	25
Muscovite	33	20		45			20	5	5	10	12
Chlorite					tr			3			
Garnet	5				tr	40	5		19	5	5
Graphite				2			5		tr		
K-feldspar	5										
Albite-Oligoclase					An_{20} 15	An_{20} 5	An_{15} 15	An_{12} 22	An_{15} 22	An_{12} 15	
Sphene	2										
Tourmaline				6							
Actinolite								5			

k=kyanite partially replaced by sillimanite.

lm=limonitic staining suggestive of former chloritoid.

1. Typical Sabattus quartz-mica-garnet schist from south nose of Sabattus Mountain. (*See* analysis 2, Table 3.)
2. Silvery muscovite schist from top of Mt. Sabattus.
3. Quartz-biotite-sillimanite schist from abandoned quarry on Dyer road south of South Lewiston.
4. Tourmaline-bearing schist from Clark-Tash quarry in southeastern Lewiston.
5. Quartz-biotite schist of Sabattus formation from contact between schist and granodiorite 1½ miles west of Sabattus on north shore of small pond (Pl. 1).
6. Garnet schist from Ray's Corner (1 mile west of Sabattus).
7. Graphite-rich schist from same locality as 6.
8. Interbedded quartzite and biotite schist from East Wales (Pl. 1).
9. Quartz-garnet schist from northwest corner of Sabattus Lake.
10. Sillimanite schist from Mt. Pisgah 1½ miles east of north end of Wilson Pond (Pl. 1).
11. Quartz-biotite-garnet-chloritoid phyllite (Winthrop formation) from west shore of Lake Maranacook, north of Winthrop.

Knots of muscovite-bearing sillimanite occur in 2½-inch beds in biotite schist and can be traced for 16 feet along the strike where they pass into a garnet-rich schist free of sillimanite.

At Ray's Corner, a mile west of Sabattus village (Pl. 1), graphite is abundant in the sillimanite facies of the Sabattus formation. Graphite was mined in this area in the late 1800's (Fisher, 1933).

Garnet-rich gneiss crops out at the northwest corner of Sabattus Lake. The gneiss is intruded by granite and basic dikes.

The Sabattus formation has been mapped along the western margin of the area. Quartz-feldspar-biotite gneiss, which includes lenses and beds of quartz-feldspar-garnet-diopside rock (Table 5, no. 10), is the oldest member of the Sabattus formation in the Lewiston area. South of Poplar Hill gray, porcellaneous rocks, rich in reddish-brown garnet and short prisms of diopside, occur in the gneiss. Lenses of similar lithology are included in the quartz-sillimanite-garnet schist on the western flank of Sabattus Mountain. The frequency of these quartz-feldspar-garnet-diopside beds in the Sabattus formation suggests some correlative value because similar types occur in the staurolite and ottrelite phyllites in the middle-grade zone of metamorphism in the Livermore and Winthrop areas.

Petrography.—Petrographic study of the quartz-biotite-sillimanite schist beds of the Sabattus formation shows biotite, either completely or partially chloritized, associated with limonite and magnetite. Actinolite is a minor accessory and is not chloritized. Narrow bands of quartz, mixed with albite-oligoclase, alternate with bands of quartz and chloritized biotite. The mode of the beds of the Sabattus formation is given in Table 6. (*See, also* Figure 4 of Plate 9, Figures 3, 4 of Plate 8.)

Garnet and sillimanite are more abundantly developed in the rocks of the low knobs at East Wales. Sillimanite prisms are grouped, bunched, or felted (Pl. 8, fig. 4). Some areas of sillimanite are completely sheathed in muscovite (Pl. 9, fig. 4). Some sillimanite occurs in quartz.

Quartz forms a large part of the schist at Ray's Corner (Table 6, no. 7) and occurs as angular to subangular, slightly fractured grains. Kyanite, partially replaced by sillimanite, occurs sparingly (Pl. 8, fig. 5). Pale yellow-brown biotite is unchloritized. Sillimanite constitutes 10 per cent of some sections and replaces kyanite and muscovite. Albite-oligoclase occurs in small amounts. Graphite, the last mineral to form, occurs in cleavages and fractures in biotite and sillimanite, and between quartz grains of the groundmass.

In the garnet-rich gneisses that crop out northward from Ray's Corner to the northwest corner of Sabattus Lake the garnets are one-eighth to half an inch in diameter. Their freedom from chlorite and the absence of biotite and feldspars are characteristic.

Thin sections of the gray, porcellaneous granulite beds or lenses show a groundmass mosaic of quartz, feldspar, corroded garnets, pyriboles, small amounts of graphite, and brown pleochroic mica. Quartz and feldspars are in a ratio of 2 to 3½ in some sections. The feldspar is near

labradorite and is not sericitized. Unchloritized garnet forms 20 to 30 per cent of the sections. Diopside, the most common pyroxene, forms 10 to 15 per cent of the rock and is slightly chloritized. Graphite is the chief accessory. No biotite is noted in the sections studied. The mode of the rock is given in Table 5, no. 10.

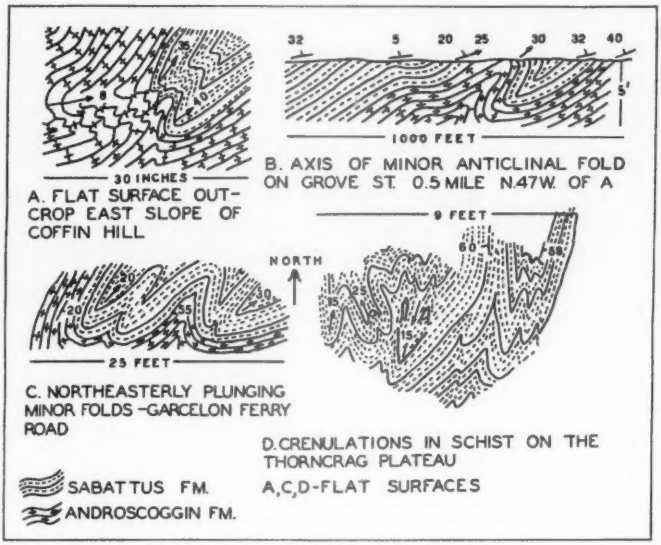
30 INCHES
A. FLAT SURFACE OUTCROP EAST SLOPE OF COFFIN HILL
32 5 20 25 30 32 40
5'
1000 FEET
B. AXIS OF MINOR ANTICLINAL FOLD ON GROVE ST. 0.5 MILE N.47W. OF A
9 FEET
NORTH
25 FEET
C. NORTHEASTERLY PLUNGING MINOR FOLDS -GARCELON FERRY ROAD
D. CRENULATIONS IN SCHIST ON THE THORNCRAG PLATEAU
A,C,D-FLAT SURFACES
SABATTUS FM.
ANDROSCOGGIN FM.

FIGURE 6.—*Small folds*

SABATTUS-ANDROSCOGGIN RELATIONS

All contacts between the lime-silicate gneiss of the Androscoggin formation and schists and gneisses of the Sabattus formation are apparently conformable. In areas of complicated folding stratigraphic relationships can be determined only by actual observations. A few outcrops in which conformability between two formations is shown are cited briefly.

(1) At East Wales (Pl. 1) quartz-mica-sillimanite schists rest conformably on lime-silicate gneiss and marble of the Androscoggin formation. (2) Half a mile east of South Monmouth the width of the highway separates outcrops of Androscoggin marble and Sabattus sillimanite schist in which dips and strikes are similar. (3) On the southeastern slope of the low hill west of Robinson Mountain quartz-sillimanite schist conformably overlies lime-silicate gneiss (Fig. 6, A). (4) The lime-silicate gneiss crops out west of the North Turner-Turner-Brettun's Mills area

(Pl. 1). On hills on the north shore of Bear Pond dips and strikes of the Androscoggin and Sabattus formations are identical. The contact is known within 100 feet. (5) Lime-silicate gneiss crops out on the northeastern slope of Norris Hill and dips beneath the Sabattus schists which form the major part of the hill. (6) In the Cobbosseecontee Pond area a small fold of Androscoggin marble is flanked on both east and west limbs by Sabattus muscovite-sillimanite schist.

WINTHROP CHLORITOID PHYLLITE

General statement.—The type locality of the Winthrop phyllite is one-quarter of a mile northwest of the village of Winthrop. There are other excellent outcrops for a quarter of a mile along the railroad on the west side of Lake Maranacook half a mile north of the village.

Two facies of the Winthrop phyllite are recognized. Small chloritoid plates characterize one facies, and staurolite and garnet crystals the other. The garnet-staurolite facies has been traced southward along the strike from Winthrop into the northeastern portion of the Lewiston quadrangle. Along the Maine Central Railroad 1½ miles southeast of the outlet of Wilson Pond it overlies conformably a middle-grade zone marble. The chloritoid facies has been traced northward along the strike into the Belgrade Lakes area where it gradually merges with the Waterville slates.

Structural relations between the Winthrop phyllite and the Androscoggin lime-silicate gneiss are shown on Plate 1.

Petrography.—The groundmass of both facies is uniformly quartz and biotite, with minor amounts of albite-oligoclase and muscovite. Small augens of quartz, with their major axes parallel to schistosity, are enclosed by muscovite. Scattered rectangular plates of nearly opaque chloritoid and elongated staurolites are not oriented. Garnet is not chloritized, although flaky chlorite is disseminated in the groundmass.

PHYLLITE NEAR BRUNSWICK

In the railroad cut of the Maine Central Railroad 2.5 miles east of Brunswick, weathered and gray streaked thin-bedded sandstones, quartzites, and chloritoid phyllites crop out. The lithology of these beds and their position above the Androscoggin lime-silicate gneiss suggest that they are the equivalent of the Winthrop chloritoid phyllite.

WATERVILLE FORMATION

General statement.—The Waterville formation (of Perkins and Smith) consists of two more or less distinct phases both of which were studied by the writer in the type areas in the Waterville region (Table 1). Dark-bluish graptolite-bearing slates are exposed in an abandoned quarry north-

west of Waterville. These slates strike northeast through Waterville and have been traced southwestward along the eastern shore of Messalonskee Lake. Black, pyritiferous slate, "rusty" mica phyllite, and pyritiferous mica phyllite are interbedded in several outcrops half a mile east of Sidney. These beds are similar lithologically and petrographically to the Winthrop phyllite.

Petrography.—The groundmass minerals of the black pyritiferous slate are not easily decipherable because of the distribution of finely divided carbonaceous material. Pyrite grains have been introduced along planes of schistosity and reach an average size of 3 millimeters. Thin rodlike plates of muscovite, 0.075 to 0.30 mm. in length, and sericite border the larger pyrites. Quartz grains are 0.10 to 0.15 mm. in size. Sections cut perpendicular to schistosity show abundant sericite.

The "rusty" mica phyllite shows a patchy distribution of biotite plates (0.02 to 0.15 mm.), some of which are in parallel intergrowth with relict chlorite. Carbonaceous particles and pyrite are not common. Biotite is pale yellow brown to yellow brown and is, in general, developed at a slight angle to schistosity.

METAMORPHISM OF SEDIMENTS

GENERAL STATEMENT

The general terms low-grade, middle-grade, and high-grade zones of metamorphism are used (Table 1) to describe the varying degrees and kinds of metamorphism that the rocks of the area have undergone. The writer uses the terms applied to zonal metamorphism as used by Billings (1937, p. 543) with slight variations. Subdivisions within the middle-grade zone (chiefly the amphibolite facies of Eskola) are made on the basis of mineral indicators used by Harker (1932, p. 209). A reference to the more recent zonal indicators advocated by Turner (1938, p. 168) is made in several cases. It was also deemed advisable to use, in part, the threefold subdivision of Harker for the middle-grade zone of Billings—namely, the biotite, garnet, and staurolite subzones.

MINERALS PRESENT

Quartz is not used as a criterion for zonal indexing because of its widespread occurrence in rocks of the area. It is lacking or sparingly developed in the marbles of the Brunswick area and in the metamorphosed limestones near Winthrop (Pl. 8, fig. 1). A moderate degree of granulation is noted in the quartz in the Taylor Brook gneiss and in the silicated facies of the marble of the Androscoggin formation.

Chlorite is not present in all the rock types of the region. It occurs in the Androscoggin formation in the slightly granulated zones in the sili-

cated facies of the marble; with scapolite and calcite in some of the lime-silicate gneisses; after biotite in the marble at Greene; with unchloritized biotite as small relict shreds in some of the sandy, biotitic schist facies of the Tacoma Lakes area; and in the groundmass of the Winthrop chloritoid phyllite. It is characteristic of the Waterville formation.

The chlorite associated with certain beds of the Androscoggin formation and the amphibolite of the Pejepscot formation might be retrograde in origin or it might be the product of hydrothermal alteration. Chlorite of the lime-silicate gneiss of the Androscoggin formation near the Tacoma Lakes is a remnant of the low-grade zone chlorite. The mineral appears to have indicative value only in the northern and northeastern portions of the mapped area.

Chloritoid occurs in the phyllites north of Winthrop, where it is associated with biotite, garnet, and staurolite, and in the phyllite east of Brunswick. Pleochroism from colorless to pale greenish yellow has led the writer to identify the mineral as chloritoid instead of ottrelite. Chloritoid is to be expected in the low-grade and middle-grade zones of metamorphism of the beds of the Waterville formation in which there was an abundance of alumina and a sufficient amount of iron oxide.

Amphiboles and pyroxenes are probable indicators of the upper part of the low-grade zone (subzones 3 and 4 of Turner) and the middle- and high-grade zones. Hornblende, variety pargasite, occurs in the amphibolite facies and the calcareous facies of the Pejepscot formation, in association with diopside, biotite, and garnet. Basic hornblende of the amphibolites is moderately uralitized. Slightly chloritized actinolite occurs in some of the marble beds of the Androscoggin formation and in some of the quartz-biotite schists of the same formation near the Tacoma Lakes. Actinolite is to be expected in dolomitic rocks and by increasing metamorphism might be converted to diopside which is characteristic of the middle-grade and high-grade zones of metamorphism. Diopside occurs in the Androscoggin formation and in the calcareous facies of the Pejepscot gneiss (Table 2, no. 2). Hornblende and augite occur in the quartz-feldspar-garnet diopside lenses in the Sabattus formation (Table 5, no. 10).

Biotite is a common constituent of most of the rocks of the area. A moderate degree of chloritization has taken place in some beds. This process is usually most marked where pegmatites have invaded the sediments and is due to hydrothermal activity. All the biotite of the thin sections studied is pleochroic in tones of yellow brown to orange or reddish brown, except in the mica phyllites of the Berwick area where green to yellow-green biotite predominates.

Turner (1938, p. 162) suggested that oligoclase be used as a zonal indicator equivalent to the garnet, and possibly the kyanite, zones of metamorphism. Albite-oligoclase occurs in the Taylor Brook gneiss, in the Pejepscot gneiss, and in the schist facies of the Pejepscot gneiss at Danville. Practically all the feldspars studied in the rocks of the Sabattus formation, with the exception of the garnet-rich gneisses and beds near granodiorite intrusions, are albite-oligoclase (Table 6, nos. 5-10). Oligoclase-andesine occurs in some of the marble of the Androscoggin formation, but the dominant feldspar is more calcic than oligoclase-andesine (Table 5, nos. 4-10).

Garnet is usually restricted to the middle-grade and high-grade zones of metamorphism, although Turner (1938) suggests that its absence from schists derived from graywacke might be due to the fact that all the chlorite present was used for forming biotite before the oligoclase (garnet) isograd was reached. Corroded but unchloritized garnets make up a large part of the quartz-feldspar-diopside-garnet lenses in the Sabattus formation. Unchloritized garnets occur in the gneiss at Ray's Corner, west of Sabattus; in the quartz-mica-sillimanite schists of the Sabattus formation; and in the chloritoid phyllite near Wayne. Chloritized garnet is found in some beds of the Androscoggin marble where graphite, scapolite, and vesuvianite are common. The mineral association indicates chlorite produced by hydrothermal action.

Staurolite, confined to the aluminous sediments of the area, occurs only in association with chloritoid, garnet, and biotite in the Winthrop phyllite in the northern part of the mapped area (Table 6, no. 11) and in the phyllites mapped as Berwick by Katz in the southwestern part of Maine.

Kyanite has been noted in minor amounts in the quartz-mica-sillimanite-graphite schist of Ray's Corner, west of Sabattus, where it is partially replaced by sillimanite (Table 6, no. 7). It is more abundant in the Windham-Cornish-Limerick area, mapped as Berwick by Katz, and in the Berwick quartz-mica phyllite near the village of Berwick in southwestern Maine.

Sillimanite occurs in moderate amounts in the beds of the Sabattus formation. It is generally restricted to aluminous sediments and indicates intense metamorphism. It has not been observed in the chloritoid phyllites near Winthrop. Some thin sections of quartz-mica-sillimanite schists show an association of slightly chloritized biotite, unaltered biotite, garnet, and sillimanite in the groundmass, and sillimanite completely enclosed by muscovite.

Graphite-bearing marbles in the Lewiston City quarry show an increase in graphite content, or show no graphite at all, when traced along or across the strike. Graphite is present in some of the pegmatites of the

area and in the quartz-mica-sillimanite schists of Ray's Corner. The writer does not believe graphite can be used as an indicator of degree of metamorphism.

SUMMARY OF METAMORPHIC CHANGES

The association of albite, yellowish-brown or green biotite, calcite, epidote, chlorite, and quartz, characteristic of the typical green schists, is found only in the area immediately around Waterville. Epidote, associated with chlorite and green biotite (Pl. 6, fig. 6), occurs at Bunganuc Landing (Pl. 1). These beds are in the lower-grade and lower-middle-grade zones of metamorphism. The sillimanite facies of the Sabattus formation can be traced northward and northeastward along the strike into rocks that carry suites of minerals indicative of less intense metamorphism.

STRUCTURE

GENERAL STATEMENT

The general structure of the area mapped is a syncline that strikes approximately N. 20° E. and plunges to the northeast. The various axes shown on Figure 7 can be followed without much difficulty. Most of the major folds and associated minor folds are shown in structure sections on Plate 1. Crenulations in the marble beds of the Androscoggin formation (Pl. 3) and in the marble and more calcareous beds of the Sabattus formation (Fig. 8) appear to be reflections of minor structures impressed on the major structure. In some outcrops (Fig. 6, D) complicated folding on a small scale is common. Fracture cleavage has been noted only in the area east of the south end of Messalonskee Lake (Pl. 1). Drag folds, relatively uncommon in the Pejepscot and Taylor Brook formations, have been studied in the Androscoggin and Sabattus formations.

STRUCTURES NEAR LEWISTON

The location of the Turner anticline (Fig. 7) is based on westerly-dipping lime-silicate gneiss and quartz-mica-sillimanite schist north and west of Bear Pond, and eastward-dipping beds of the same formations at and southwest of Turner. This anticline has been traced northeastward to Livermore Falls (Fig. 1).

The superior hardness of the older gneisses of the Pejepscot formation arched up by the Auburn anticline is responsible for the topographic feature known as Merrill Hill in Auburn. The marble and lime-silicate gneiss of the Androscoggin formation dip away from this axis in all directions except southward. Hanley has mapped the lime-silicate gneiss and the Sabattus schists west of the Auburn anticline in the Poland quadrangle. The northeasterly plunge of the Auburn anticline accounts for the absence of Taylor Brook gneiss beds north of Gulf Island (Pl. 1).

Minor rolls in structure on the north side of Auburn toward East Auburn account for the sinuous contact between the Taylor Brook-Androscoggin formations north of Lewiston.

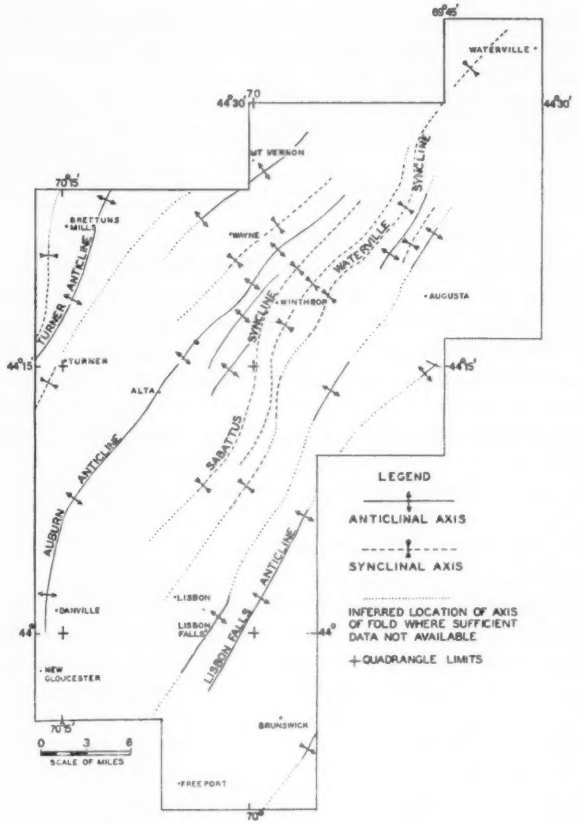

FIGURE 7.—*Structure map of Lewiston area*

The Lewiston City quarry is near the southwestern end of the Sabattus syncline. Recumbent folds in the quarry and elsewhere in the Lewiston area complicate the structure of the region. Remnants of marble in granite southeast of Lewiston and of Sabattus schist in granite half a mile south of South Lewiston show the former areal extent of the syncline. Numerous plunging folds in the Sabattus formation north and east of

Lewiston indicate complicated folding in the Sabattus syncline northward along Robinson Mountain to Sabattus Mountain.

Lime-silicate gneiss and quartz-feldspar-biotite-garnet schist are involved in three, small, northeasterly-plunging folds along the eastern shore of Sabattus Lake (Pl. 5, fig. 1). The average strike of the axes of the folds is N. 23° E., and the plunge is 34° NE. Sabattus Mountain

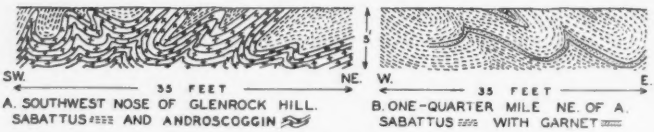

FIGURE 8.—*Structural sections in Sabattus formation*
Glenrock Hill, two miles southwest of Greene

is developed along the strike of the argillaceous and arenaceous sediments of the Sabattus formation which plunges northeastward. A granite mass cuts the sediments on the north side of the high point of the hill. The type localities of the quartz-biotite schist and quartz-mica-sillimanite schist of the Sabattus formation at East Wales and the "Knobs" area are located on the eastern flank of the syncline. Marble beds similar to those of the Lewiston City quarry crop out in strongly crenulated beds (Pl. 3, fig. 2) 1½ miles northeast of East Wales. These folds plunge 18° NE. under the Sabattus schists which form a low ridge to the northeast.

A steep escarpment borders the eastern and southeastern faces of Sabattus Mountain and the ridge northeast of East Wales. No slickensided surfaces or displaced beds have been found along the escarpment.

The axis of the Sabattus syncline can be traced northeastward from Lewiston, through Sabattus Mountain, and into the area between Winthrop and East Winthrop. Half a mile north of East Winthrop the quartz-biotite-sillimanite schists (similar to those of East Wales) are interbedded with typical bluish calcareous shales of the Waterville formation. Minor folds in this area plunge south-southwestward.

The axis of the Sabattus syncline and the axis of the anticline shown on Figure 7 between the Sabattus and Waterville synclines in the Winthrop area trend more strongly northeastward as they are traced northward from the Winthrop area.

LISBON FALLS ANTICLINE

The axis of this anticline has been mapped southwestward toward Freeport because of outcroppings of Androscoggin marble north of that town

(Pl. 1). The eastern flank of the Lisbon Falls anticline extends to Bunganuc Landing where an epidote-chlorite schist either forms the upper part of the Pejepscot formation or rests conformably on that formation. Two miles east of Brunswick phyllites similar to the Winthrop phyllite crop out in the Maine Central Railroad cut and mark the western flank of the syncline to the east of the Lisbon Falls anticline. The northeasterly extension of the Casco Bay group of Katz lies within this syncline.

A minor anticlinal roll on the western flank of the Lisbon Falls anticline is shown in Figure 7 and is indicated by outcroppings of marble of the Androscoggin formation in Pejepscot terrain.

LOCAL CHANGES IN STRUCTURE

Numerous inclusions of metamorphosed sediments that occur in the granite and pegmatites throughout the Lewiston area have been studied. The general structure of sedimentary beds included in the igneous masses agrees closely with the observed regional structure. There has been little reorientation of the enclosed blocks. An excellent example of changes in structure due to the invasion of the Pejepscot gneiss by pegmatite is illustrated in Figure 10 F. The pegmatite shown is sheeted, and sheets dip 20° SW. and strike N. 45° W. Major fractures in the pegmatite strike N. 71° E. and dip 65° NW.

CORRELATION OF FORMATIONS

BASIS OF CORRELATION

General statement.—Several methods are available in establishing relationship between formations in different areas. Some of these methods are: (1) correlation on the basis of well-preserved fossils; (2) comparison of chemical and mineralogic content of the beds; (3) similarity of sequence of formations in the areas; (4) establishment of structural conformity between the areas; and (5) acceptance of the published age of the formations.

The first method is not applicable in the immediate Lewiston area for no fossils have been found by the writer. The fifth method is not acceptable to the writer because the published geological map of Maine (Fig. 2) does not present results of detailed studies in the area, and because a comparison of this map and Plate 1 will show that many areas mapped previously as igneous rocks are areas of high-grade metamorphosed sediments. It seems best, therefore, to use a combination of the remaining methods.

Evidence for correlating the Sabattus formation of this paper with the Waterville formation of Perkins and Smith is based soundly on simi-

larity of materials (Table 1), similarity of sequence of formations in scattered areas, and on structural continuity between the type localities of the Sabattus formation and the Waterville formation (Fig. 9, locs. J and Sw).

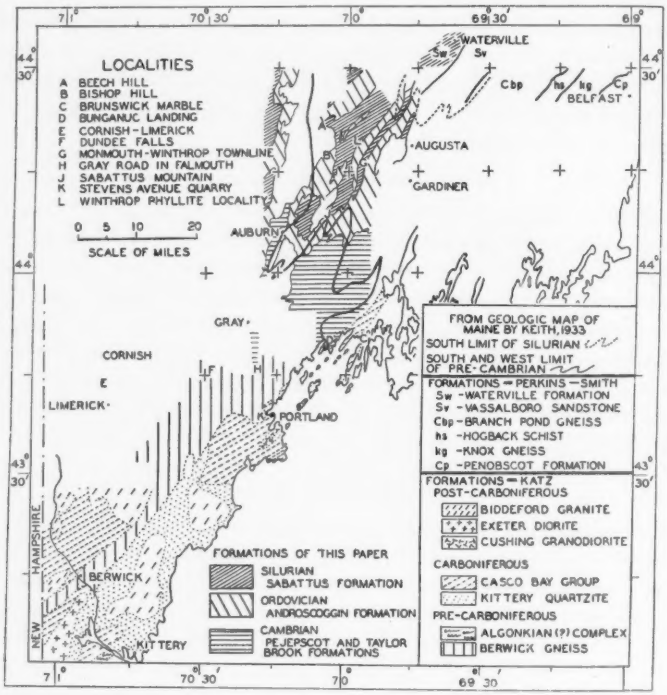

FIGURE 9.—*Correlation of formations*

Sabattus-Waterville correlation.—The mineral content of the Sabattus and Waterville formations is shown in Table 1. Changes in mineral content from minerals characteristic of the high-grade zone of metamorphism to minerals characteristic of the low-grade zone have been established along the line of strike of the two formations.

The Sabattus formation can be followed from Lewiston northeastward along the strike to East Winthrop (Pl. 1). Approximately 4 miles southwest of East Winthrop and half a mile west of the first "e" in Cobbosseecontee Pond, "rusty" pyritiferous quartz-mica schists, weathered to a distinctive golden yellow, crop out and can be traced to East Winthrop.

A quarter of a mile south of the letter "t" of Winthrop in East Winthrop, a flat surface exposure shows characteristic ridge and valley "topography" on inter-bedded calcareous and argillaceous rocks similar to the Waterville formation. A mile northeast of East Winthrop, southwestward-plunging beds similar to those described at East Wales crop out. Interbedded quartz-biotite schists and thinly bedded quartzites crop out from this locality northward for 4 miles. Glacial drift covers bedrock in this region. In the locality of the group of small ponds 1½ miles west of Sidney Bog quartz-mica schist and quartz-biotite schist of the Sabattus formation are interbedded with bluish-black pyritiferous weathered slates of the Waterville formation. Slaty cleavage is first observed northward along the strike in and around Sidney Bog and on the southeastern side of Messalonskee Lake.

The western flank of the Sabattus syncline has been traced northeastward from Lewiston to Norris Hill (Pl. 1). Northeastward from Norris Hill along the strike through Winthrop and the Maranacook Lake area, chloritoid phyllites crop out and can be traced to the northeastern edge of the mapped area where they are covered by glacial drift. Between Maranacook Lake and Readfield, an anticlinal roll (Pl. 1) exposes the Androscoggin formation. Northwest of this anticlinal roll sillimanite is present in some of the beds of the Sabattus formation.

The occurrence of sillimanite-bearing schists at the southwestern end of the Sabattus syncline near Lewiston, the change to staurolite and chloritoid schists and phyllites in the Winthrop area, the appearance of slaty cleavage in rocks of the same lithologic character in the Sidney Bog-Messalonskee Lake area, and the regional trend of the Sabattus formation traced through these successively lower zones of metamorphism into the graptolite-bearing slates of the Waterville region lead the writer to class the Sabattus formation as the southwestern equivalent of the Waterville formation of undisputed Silurian age.

Androscoggin-Vassalboro correlation.—The writer studied the Vassalboro formation with Perkins and Smith and pointed out to them that the formation contains numerous calcareous beds. The formation ("Sv" on Fig. 9) outcrops in the channel of the Sebasticook River (the river that enters the Kennebec from the east, south of Waterville) half a mile from the type locality of Perkin's Waterville formation. The Vassalboro formation is more calcareous in the exposures in the Sebasticook River than the Waterville formation is in its type locality.

Increase in the intensity of metamorphism of the Vassalboro formation produced the lime-silicate gneiss of the Androscoggin formation. The

Androscoggin formation of the Tacoma Lakes area was identified by Perkins and Smith as the Vassalboro formation.

The occurrence of typical lime-silicate gneiss, with slight thicknesses of marble, makes the identification of the Androscoggin formation unmistakable. It has been traced in conformable relation with the Sabattus formation northward from Lewiston on both flanks of the Sabattus syncline. The Hallowell granite (Pl. 1) nearly cuts off the Androscoggin east of Cobbosseecontee Pond. Isolated patches of lime-silicate gneiss occur in the granite in the vicinity of Manchester and Augusta. One mile south of Sidney, chloritic limestone in the lower-middle grade zone of metamorphism crops out in an area mapped as Vassalboro by Perkins. North of Augusta, on the east bank of the Kennebec River, lime-silicate gneiss has been mapped for 2½ miles along the strike in Vassalboro terrain.

Large masses of igneous rocks, principally granodiorite, and glacial drift obscure the full width of the belt of the Androscoggin formation along the western belt of the syncline. The formation has been traced through Greene, Alta, and Curtis Corner to the hornblende gabbro knobs south and east of Androscoggin Lake. In the Beech Hill section, 1.8 miles west of the north end of Pocasset Pond, marble of the Androscoggin formation lies conformably below interbedded schists and quartzites of the Sabattus formation. Between Readfield and Bowen Hill (Pl. 1) repetition of beds of lime-silicate gneiss of the Androscoggin formation and fine-grained quartz-biotite phyllite of the Winthrop formation crop out.

At East Wales, near Sabattus Mountain, and at Beach Hill, near Wayne, quartz-biotite schists, interbedded with thin quartzites, occur at or near the base of the Sabattus formation and overlie conformably the marble beds near the top of the Androscoggin formation. The quartz-biotite schists, interbedded with thin quartzites, are here correlated with the interbedded sandstones and shales that Perkins has described as transitional between the Waterville and Vassalboro formations.

Pejepscot correlatives.—The Pejepscot formation can be traced northward along the eastern limit of the area shown on Plate 1, through Bowdoin Center toward Litchfield Corners. In the vicinity of Gardiner, there are scattered outcrops of both the Androscoggin and the Pejepscot formations, the latter occurring principally in the southeastern part of the section toward 44°10′. The Androscoggin formation has been mapped as far east as Richmond Corner (half a mile due east of the south end of Pleasant Pond). The quartz-feldspar-biotite gneiss of the Pejepscot formation is, in part at least, equivalent to the Branch Pond formation of Perkins. This correlation is suggested by the average mineralogic

composition of the Pejepscot gneiss and its position stratigraphically below and geographically east of the Androscoggin formation.

Correlation with Berwick of Katz.—The correlation with formations mapped by Katz is based on similarities between the Pejepscot and Androscoggin formations of this paper and the Berwick and Casco Bay group of Katz. The sequence of formations in southwestern Maine, as given by Katz (1917, p. 166), is as follows:

CARBONIFEROUS (Pennsylvanian?)	
Casco Bay group	
Mackworth slate	
Jewell phyllite	
Spurwink limestone	
Scarboro phyllite	(southeastern New Hampshire)
Eliot slate	Eliot slate
Diamond Island slate	Towow formation
Spring Point greenstone	Rindgemere formation
Cape Elizabeth formation	Gonic formation
Kittery quartzite	
PRE-CARBONIFEROUS	
Quartzites with rhyolite flows, etc.	
Slates, schists, and hornblende schists	
Quartzites and graywacke gneiss (Algonkian?)	
Berwick gneiss	

The Berwick gneiss includes graywacke gneiss, quartzites, micaceous quartzites, mica schists, metadiorites, argillites, schists, and light-blue crystalline limestone. The most abundant rock is the bluish-gray graywacke gneiss which includes a quartz-feldspar-biotite gneiss of high degree of crystallinity and abundant metamorphically developed biotite. Katz states that the most distinctive feature of the Berwick is the recrystallization of the graywacke into nonfoliate dioritelike aggregates of quartz-feldspar-hornblende-garnet selvages, lenses, and spheroidal and irregular patches. These aggregates are lithologically the same as the lime-silicate gneiss of the Androscoggin formation. The quartz-feldspar-biotite gneiss is identical with the Pejepscot gneiss.

At Bonny Eagle, on the Saco River, 11½ miles southeast of Limerick (Fig. 9), the writer and Edward S. C. Smith studied the bedrock of the Saco River when the channel was dry during the building of a dam. The Berwick gneiss exposed in the river is essentially the same as the lime-silicate gneiss, with interbedded marble, of the Androscoggin formation. The metadiorite of Katz, in this area, is the same lithologic unit as the lime-silicate gneiss of this paper.

Six miles south of Cornish (Fig. 9, loc. E) lime-silicate gneiss, with abundant epidote, sahlite, and diopside, and well-developed crystals of

vesuvianite and brown garnet, crops out along the Limerick-Cornish highway in an area mapped as Berwick by Katz. The general lithology of these beds of lime-silicate gneiss is essentially the same as in the Lewiston area at Robinson Mountain.

Scattered outcrops northwest of Berwick have been studied by the writer. Thin sections from these outcrops show a quartz-muscovite ground mass with subordinate amounts of albite-oligoclase. Large plates of unchloritized yellow-green biotite are associated with chloritoid and staurolite (1.5 mm. long) and lesser amounts of kyanite. Garnet is not chloritized. The hand specimens of these rocks is a lustrous quartz-mica phyllite darker in color than the golden yellow quartz-muscovite-sillimanite schist of the Sabattus formation. The mineralogy of this facies of the Berwick formation suggests that this is middle-grade zone Sabattus overlying conformably the lime-silicate portion of the Berwick gneiss.

Staurolite-garnet schists, with minor amounts of kyanite, dip westward near the northwestern margin of the Berwick formation east of Cornish and Limerick (Fig. 9, loc. F). A mile east of these westward-dipping schists, typical lime-silicate gneiss of the Androscoggin formation crops out.

Correlations in Portland area.—The Stevens Avenue quarry (Fig. 9, K) is worked in eastward-dipping beds of lower-middle grade limestone and interbedded shales belonging to the Berwick of Katz. Actinolite in these limestones is associated with garnet and albite-oligoclase.

Numerous natural and artificial exposures of the Pejepscot gneiss have been studied along U. S. Highway No. 1 from Portland through Freeport to Brunswick. This area must be located in the northeastward extension of the Berwick of Katz. Reconnaissance mapping by the writer and J. B. Hanley shows that the Pejepscot formation extends northward from Portland toward Lewiston and Brunswick and must include formations included in the Berwick, Kittery, and Casco Bay group of Katz.

Brunswick area.—Hornblende-epidote-chlorite schist crops out at Bunganuc Landing (Fig. 9, D) conformably above the Pejepscot gneiss. This schist, which is lithologically the same as the Spring Point greenstone of Katz, appears to be the southwestern continuation of the hornblende-rich gneiss which overlies the marble at locality C of Figure 9. Phyllites, slates, and limestone of the Casco Bay Group overlie the Spring Point greenstone in the Portland area.

The Jewell phyllite of the Casco Bay group is characterized by its silky sheen and its metacrysts of ottrelite, garnet, and staurolite. In these

features it is the same as the Winthrop phyllite which carries the transition from the Sabattus sillimanite schist into the Waterville slates in the Winthrop area. Rocks of Jewell phyllite lithology crop out in the railroad cut of the Maine Central Railroad, 2 miles east of Brunswick, on the south side of the Androscoggin River (Pl. 1). One and one-half miles south, and half a mile east of the railroad cut outcrop, the author has traced a belt of marble (Fig. 9, loc. C) 20 feet thick for more than 1½ miles along a north-south strike. The phyllite of the railroad cut belongs within the limits of the northeastward extension of Katz' Carboniferous. The marble of locality C, Figure 9, lies east of this Carboniferous extension and dips westward toward Brunswick conformably above a hornblende-rich gneiss. The formations mapped by Katz must therefore occupy a syncline east of the Lisbon Falls anticline.

Summary of correlation.—The heavy line in Figure 9 which shows the northern limit of pre-Cambrian gneisses on the geologic map of Maine (Keith, 1933) can no longer be used as a boundary line. All the formations described in this paper cross this line in a northeast-southwest direction without any noticeable change in the degree of metamorphism.

The chief difference between the formations of the Lewiston-Winthrop area and of the Winthrop-Waterville area is one of degree of intensity of metamorphism. The general trend of the Berwick of Katz and its general structure and lithologic characteristics are suggestive of equivalence with the Pejepscot gneiss, the Taylor Brook gneiss and part, at least, of the Androscoggin formation. The lime-silicate gneiss of the Androscoggin formation, especially in its quartz-biotite facies at the Tacoma Lakes, appears to be the equivalent of the Vassalboro of Perkins and Smith and the Kittery quartzite of Katz.

IGNEOUS ROCKS

GENERAL STATEMENT

Igneous rocks form approximately 20 per cent of the area shown on Plate 1. The contacts between these igneous rock masses and the intruded sediments and between the igneous rock masses and the glacial drift are approximate. Granodiorites form more than one-third of the area of igneous rocks, granites and pegmatites are next in importance, gabbroic rocks are more or less restricted to the vicinity of Androscoggin Lake, and soda syenites and litchfieldite have been described from the east-central portion of the area.

The igneous rocks have not been studied in detail. No chemical analyses are available. The distribution of the rocks, their mineral composition, and their relation to the invaded sediments are described briefly.

GRANITES AND PEGMATITES

The main area of granites and associated pegmatites is in the southwestern, south-central, and southeastern portions of the mapped area. There are numerous isolated knobs of these rocks scattered throughout the southern half of the area (Pl. 1) but these will not be described in detail.

The granite of the Woodbury Hill area is a medium- to fine-grained, pinkish, muscovitic granite which invades the formations in the southern part of the area. North of Woodbury Hill the granite is coarser-grained and grayer. Southeast of Lewiston granite genetically related to the granite of Woodbury Hill crops out in low hills on the northeast side of the Androscoggin River. Blocks of marble of the Androscoggin formation occur in these granite knobs. Farther up the slopes of these knobs remnants of quartz-feldspar-biotite gneiss of the Sabattus formation is enclosed in the granite. Pegmatite facies of the same granite intrude the Pejepscot gneiss in the Brunswick-Durham-Bunganuc Landing area.

The invasion of the granite bodies in the Topsham and Brunswick region is responsible for the thorough soaking of the Pejepscot gneiss which, in places, is difficult to distinguish from a true granite or granite gneiss.

The associated pegmatites of the Lewiston and Topsham areas are important economically and are quarried in many localities for feldspars and by-product gem stones.

The writer has traced the granites south of Lewiston through Woodbury Hill to New Gloucester toward Portland and correlates this granite with the Westbrook granite of Katz.

The mode of the granite of Woodbury Hill (Table 7, no. 3) shows moderately sericitized microcline as the chief feldspar. The plagioclases show a much higher degree of sericitization. Quartz is moderately corroded but not strained.

Several textural and mineralogical varieties of the Topsham granite have been observed in the field. In general the granites of this area are medium- to coarse-grained, with finer-grained types occurring principally near Pejepscot. Some of the outcrops show strong foliation of biotite plates; others show a strongly porphyritic facies. In all areas, the granite of the Topsham region resembles closely in texture, color, and mineralogical composition the granite of the Woodbury Hill area.

Microscopic study of the granites of the Topsham region shows irregularly shaped quartz grains which average 0.25 millimeter and attain a maximum size of 1.2 millimeters. Fractures in the quartz grains are continuous through several grains of quartz and adjacent feldspar but do not pass through the interstitially developed biotite. Polysyntheti-

TABLE 7.—*Mode of some igneous rocks of Lewiston region*

Rock name	1	2	3	4	5	6	7	8	9	10
No. of sections	3	2	5	3	2	4	1	2	2	3
Quartz	30	25	30	23	45	30	35	22		
K-feldspar	35	40	35 m	15		15	18 m	19		
Albite-oligoclase	An_7 15	An_9 10	An_{10} 25			An_{10} 25	An_{17} 20	An_{12} 37		
Oligoclase-andesine				An_{22} 30 s	An_{20} 22	An_{30} 10				
Andesine-labradorite									An_{48} 40	An_{45} 30
Labradorite-bytownite									An_{60} 10	
Muscovite	10	15	5	15	10		12	5		
Biotite	5		2	8 ch	15 ch	15 ch	15	10	10	20
Garnet	(a)			(a)			(a)	5		
Zircon	(a)	(a)	(a)		3	(a)	(a)		(a)	(a)
Magnetite		(a)				5				
Tourmaline		(a)					(a)			
Chlorite			(a)		5				·	
Hornblende				(a)		5	(a)		40	35
Calcite						2				5
Beryl							(a)			
Sillimanite								(a)		
Apatite									(a)	(a)

a = accessory minerals
ch = chloritized, in part
m = chiefly microcline
s = largely sericitized

1. Sabattus granite; 2 miles south of Leeds Junction (Pl. 1).
2. Topsham granite; 1 mile north of Topsham (Mt. Ararat region) (Pl. 1).
3. Woodbury granite area; random specimen east and northeast of Danville (Pl. 1).
4. Granodiorite from Hedgehog Hill specimens from near contact with granodiorite gneiss, northwest side of Sabattus Lake.
5. Granodiorite gneiss; 2 miles southwest of Sabattus village and south of granodiorite area of number 4 above.
6. Granodiorite of Turner Mountain area; random specimen from between Turner and locality 13 on Plate 1.
7. Granodiorite from Keen's Bridge on Androscoggin River between Leeds and North Turner.
8. Sillimanite-bearing granodiorite; specimen from Merrill Hill (Pl. 1).
9. Hornblende gabbro; small roadside exposure 1½ miles southwest of Norris Hill on Plate 1, along margin of sand plain.
10. Hornblende gabbro from typical specimens at Morrison's Heights, south of Wayne (Pl. 1).

cally twinned albite-oligoclase is less abundant than the untwinned plagioclase. Isolated patches of biotite plates, 0.64 to 0.28 millimeter, include haloed zircons. Rutile needles or rods are more common in the granites of the Topsham region than in granites of other localities mapped by the writer. Magnetite is a common accessory of the granite in the Topsham region. It is more abundant in biotite-free portions of the thin sections than it is near unchloritized biotite. The mode of the granite of the Topsham area is shown in Table 7, number 2.

The granites of the Topsham area are of special interest. Gonyer (1937) analyzed a sample of samarskite from the granite in this region and stated that the age is distinctly Carboniferous.

On the north slope of Sabattus Mountain a granite cuts the Sabattus formation. This granite is a light to nearly white, weakly gneissoid granite sprinkled with small, well-crystallized, reddish garnets and one-eighth-inch biotite plates. The chief mineralogical difference between the granite of this area and the granite of the Woodbury Hill and Topsham areas is in the kind and amount of feldspar (Table 7, no. 1).

Under the microscope, the biotite is a dark cherry-red and encloses numerous zircons with pleochroic haloes. Ends of the biotite are not shredded or feathered against the contacting minerals. Muscovite, associated with biotite, either cuts across the black mica or penetrates along the cleavages. No magnetite or other opaque minerals are associated with the unlimonitized and unchloritized biotite.

GRANODIORITES

Granodiorite covers approximately 70 square miles of the area mapped, cropping out principally in the western and northwestern portions of the Lewiston area. The granodiorite has been studied in several portions of the area. The modes of the average specimens are given in Table 7, numbers 4, 5, 6, and 7.

The granodiorite of Clark Mountain, Merrill Hill, and near-by localities is a medium- to coarse-grained rock in which plagioclases are more abundant than potash feldspar and in which small reddish-brown garnets can be seen with the naked eye. There is less biotite in the granodiorites east of the Androscoggin River than in the same rock type at Poplar Hill, west of the river (Table 7, nos. 6 and 8). No gneissic tendency is shown by the micas in the Clark Mountain and Merrill Hill localities, although such tendency is noted in masses farther north along the Androscoggin River.

Microscopic study of the granodiorite from the southern part of Merrill Hill shows a hypidiomorphic granular to extremely cataclastic texture in some portions. The quartz of most of the thin sections is moderately

fresh and not highly fractured; zones of smaller individual grains represent a slight amount of granulation. Quartz averages 0.2 millimeters, with maximum grain size 2.5 millimeters. The feldspars are predominantly albite-oligoclase (Table 7, nos. 7, 8). Sericitization of the feldspar is moderate. Biotite occurs as scattered, irregular patches that are bleached dirty yellow brown to very weak reddish brown and are dotted with small grains of magnetite. Muscovite, which is less abundant than the biotite, occurs in scattered plates and interstitially; it shows extremely ragged borders especially against the biotite which it appears to have replaced. The muscovite is commonly associated with zones of granulated quartz.

The granodiorite of the Poplar Hill area is moderately coarse-grained. Biotite, quartz, feldspar, minor amounts of muscovite, and small reticulated patches of diopside are identified with the naked eye. Under the microscope this granodiorite does not differ much from that on the east side of the Androscoggin.. Pericline and albite twinning are noted in unsericitized feldspar. Myrmekitic feldspar and some slight bending of twinning lamellae are noted.

The granodiorite of Hedgehog Hill, a mile southwest of Sabattus, is of interest because (1) on the northwest nose of the hill near the shore line of the small pond shown on the map the country rock is the Sabattus formation; (2) on the south and southeast side of the hill, near the contact with the granodiorite gneiss, marble of the Androscoggin formation dips westward into the hill, and (3) an irregularly shaped mass of granodiorite gneiss, approximately 1 square mile in area, crops out on the southern side of the hill. Some monumental stone has been quarried from this granodiorite which is not uniform in texture. Pegmatite veinlets are injected into the granodiorite which appears to be more coarsely grained near these injections. Contacts between the fine- and coarse-grained facies are marked with biotite in bunches and stringers. Garnet is abundant.

Thin section study shows some striking differences between the granodiorite of this and other areas. In the Hedgehog Hill granodiorite the development of sericite in cross-lined pattern suggests original microcline in small amounts. Micrographic and myrmekitic intergrowths are more common than in the other granodiorites. Chlorite is more abundant in this rock than in any other rock of the area. The mode of the granodiorite is shown in Table 7, no. 4.

HORNBLENDE GABBRO

The hornblende gabbro of the area is best developed in the vicinity of Androscoggin Lake. There are but three areas in which the writer has

seen outcrops of these gabbroic rocks. The chief problem in mapping the areas is one of whether or not the masses found are actual outcrops or merely "house-size" boulders. Such blocks, 40 to 50 feet in length and width and 20 to 25 feet in height, may resemble true exposure of igneous masses, when buried in drift. Hornblende gabbro actually crops out in the areas so designated on Plate 1.

Morrison Heights, east of Androscoggin Lake and south of Wayne, is a gabbro mass that has been intruded into lime-silicate gneiss. Small gabbro knobs crop out north of Androscoggin Lake and on Bishop Hill south of the lake.

Microscopic study shows moderately basic hornblende, slightly limonitized but not greatly chloritized, constituting about 35 per cent of the gabbro (Table 7, no. 10). Biotite, deep reddish brown and moderately chloritized, is in the ratio of 1 to 2 with the hornblende. The plagioclase is moderately calcic, fairly fresh, and constitutes about 30 to 50 per cent of some of the sections.

One and one-tenth miles south of Leeds Junction (Pl. 1) gabbro crops out in a small roadside exposure in which hornblende crystals reach a maximum size of 4 inches (Table 7, no. 9).

SYENITE

Litchfieldite and soda syenite crop out in the area east of the Litchfields and were described by Daly (1918). The syenites which occur in short, lenticular pods or masses have produced no marked contact effects on the metamorphosed sediments. Daly expressed the belief that intrusion occurred after metamorphism. Soda and biotite syenites are associated with the litchfieldite in the type localities. It is significant to note, in view of the conclusions reached by Daly, that the northeast extension of the metamorphosed limestones of the Tacoma Lakes area would pass into or near the terrain of the syenites.

GRANITE GNEISS

General statement.—A coarse-grained granite-gneiss, shown as "gg" on Plate 1, 1½ miles southwest of Sabattus village appears to be genetically related to the granodiorite of the Hedgehog Hill area. Hills formed by the gneiss have steep south-facing escarpments which show no slickensided surfaces.

Description.—The gneiss is light in color with a moderate amount of biotite in discontinuous streaks. Under the microscope these biotite plates are 4 to 5 times as long as wide. Magnetite, associated with the biotite, is not so common as in the granodiorite. Patches of chlorite, completely surrounded in some cases by magnetite, include small, radiating rods or

needles of rutile. Quartz occurs in small areas or in augens of well-formed grains not optically continuous and only slightly strained. The feldspar is oligoclase-andesine (Table 7, no. 5).

SEDIMENTS IN IGNEOUS ROCKS

The inclusions of sedimentary rocks in the igneous masses present an opportunity to study the former areal extent, the changes in structure, and the changes in lithology of the enclosed rocks. The results obtained in the study of some typical inclusions are described briefly.

(1) A remnant of marble of the Androscoggin formation, 12 feet thick across the beds and 8 feet long, is included in the granite half a mile south of the Clark-Tash quarry near Lewiston. The lithology and mineralogy of the included marble is the same as in the Lewiston City quarry. The structure of the blocks reflects the regional structure. Three other isolated blocks of marble are included in granite farther up the slope of the hill. None shows any marked degree of contact metamorphism produced by the invading granite.

(2) A remnant of quartz-feldspar schist of the Sabattus formation occurs in the granite near the base of the abandoned Clark-Tash quarry, half a mile north of the marble blocks near the Lewiston City Farm. The structure of the block conforms to the regional structure. Black tourmaline is abundant in the schist (Table 6, no. 4).

(3) Typical quartz-muscovite-biotite-sillimanite schist of the Sabattus formation is completely enclosed in granite in the abandoned Dyer quarry south of South Lewiston. There is no apparent difference between the schist of this area and similar schists of the Sabattus area where no igneous outcrops occur.

(4) Typical quartz-feldspar-biotite gneiss of the Sabattus formation crops out in a narrow and shallow ravine on the northwest slope of Stony Hill, 1.3 miles southwest of Merrill Hill. The largest block in the granodiorite is not more than 1½ feet long and 8 inches thick. The granodiorite here carries a moderate amount of sillimanite associated with muscovite. Some of the prismatic forms of sillimanite are transected by muscovite.

(5) A block of sillimanite-bearing schist crops out on the southeastern nose of the same hill. In both these localities there is close agreement between local and regional strikes and dips.

EFFECTS OF IGNEOUS ROCKS ON INVADED SEDIMENTS

Granitization and lit-par-lit injections are common in the southern third of the mapped area. Field and laboratory study indicates that a gneiss, probably an original graywacke, has been impregnated in varying

degrees to produce the Pejepscot gneiss, which in places resembles an orthogneiss. Bastin (1911, p. 48) noted that the pegmatite of the Danville area graded with perfect crystallographic continuity into a fine-grained granite gneiss. Beds of the mica schist facies of the Pejepscot gneiss, between sill-like masses of pegmatite, in the railroad cut north of Danville (Fig. 10, J) show no evidence of absorption, although lit-par-lit injections of quartz are common in the schist.

SILICEOUS DIKES

Pegmatites in dikes, sills, and irregular masses and aplitic dikes invade all the sediments of the area. The pegmatites are younger than the sediments and the metamorphism of the area and are older than the basic dikes. Large masses of graphic pegmatitic granite crop out in Auburn, Robinson Mountain, and in the Topsham area.

The principal minerals of the pegmatites are potash and soda feldspar (orthoclase, cleavelandite, and microcline), quartz, muscovite, biotite (chloritized in some areas), black tourmaline, lepidolite (prominent at Mt. Apatite and Topsham), red, blue, and green tourmaline and beryl (at Mt. Apatite), topaz, and gahnite (at Topsham).

In two localities, dikes of slightly gneissoid granite cut the pegmatites. One of these dikes is shown in Figure 4; the other cuts a pegmatite in lime-silicate gneiss a quarter of a mile west of the Franklin quarry in the eastern part of the city of Auburn.

BASIC DIKES

General statement.—Olivine-bearing and olivine-free basic dikes crop out in the southern part of the area mapped. No detailed study has been made of all the basic dikes, but a few generalizations will be made. The mode of occurrence of the basic dikes is shown in Figure 10. The widest dike studied is 25 feet wide and it is one of a group that cuts the schist facies of the Pejepscot near Danville. Numerous narrow basic dikes cut the marble of the Androscoggin formation in the Lewiston City quarry (Fig. 10, K). These dikes were numbered from west to east to facilitate field study and are described briefly in Table 8.

Trend.—The dikes studied have followed fractures. The average trend of the dikes is N. 50° E. to N. 70° E., although there are several dikes which trend beyond these limits, as in the northwest trending basic dike at Robinson Mountain.

No basic dikes were exposed in the working face of the Martin quarry when an earlier study was made by the writer (Fisher, 1936). In 1937 the quarry face had been driven back into the hill for an additional 20 feet along the dip of the marble, exposing a 12-foot basic dike. This

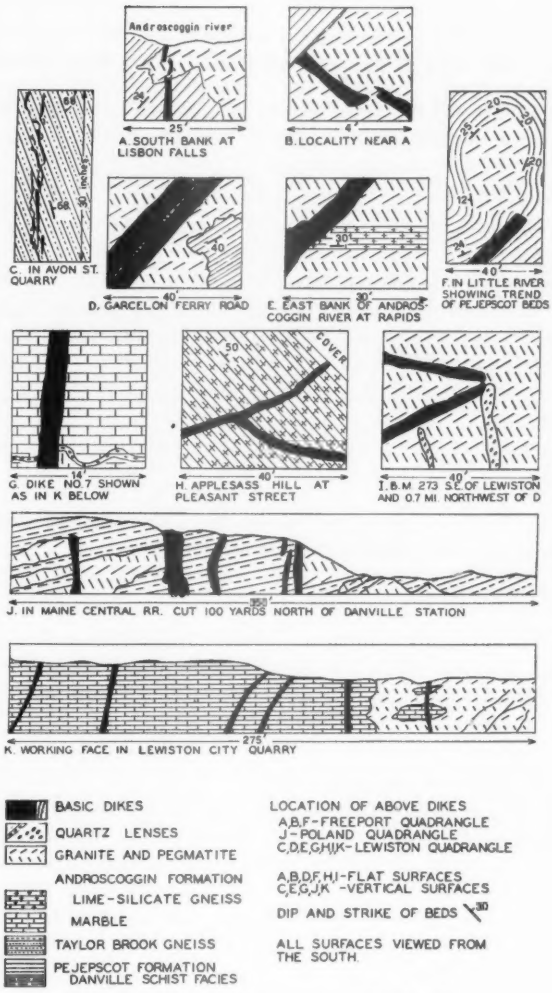

FIGURE 10.—*Mode of occurrence of basic dikes*

dike strikes N. 21° E. and dips 52° SE. There is no evidence of faulting in the quarry.

Few of the basic dikes depart radically from the trend observed at the outcrop. Cross-cutting of pencil dikes on a small scale is shown in

Figure 10, C. Cross-cutting of dikes is suggested in Figure 10, I. Curvature of exposed dikes was seen in only a few places (Fig. 10, A, J). Branching dikes were observed in only one locality (Fig. 10, H).

Petrography.—All the thin sections studied show extremely fine-grained, and for the most part irresolvable, groundmasses (Pl. 7, figs. 3, 4) in

TABLE 8.—*Thickness of basic dikes in Lewiston City quarry*

Dike no.	Width ft.	Width in.	Strike Dip	Distance to next dike in feet
1	2		N. 52° E., 80° NW.	15
2[a]	3	5	N. 56° E., vert.	50
3	2	8	N. 58° E., vert.	31
4[b]	2	11	N. 63° E., 65° NW.	46
5[a]	2	5	N. 57° E., 80° NW.	63
6	2	2	N. 56° E., 60° NW.	19
7[c]	2	6	N. 51° E., 60° NW.	44
8[d]	1		N. 59° E., vert.	39
9[e]	1	4	N. 61° E., 80° SE.	12
10	2	8	N. 53° E., vert.	62
11	1	2	N. 51° E., vert.	30
12		8	N. 55° E., 70° NW.	30
13	1	2	N. 60° E., 75° NW.	25
14		7	N. 51° E., 70° NW.	40
15	14		N. 60° E., vert.	..
av.	2	8	N. 56° E., 80° NW.	36

a = Chilled contacts (Plate 7, figure 2).
b = multiple dike.
c = olivine phenocrysts.
d = offset about one foot to west near base.
e = composite dike.

which are included calcic plagioclases in thin lath-shaped crystals and olivine phenocrysts altered to serpentine and talc and in some sections rimmed by pyroxene plates and limonitic stains. Hornblende is present in small amounts and is only slightly uralitized. Magnetite and calcite are the most common accessories.

In the typical olivine-bearing dikes, olivine is replaced almost entirely by aggregates of fibrous serpentine and some talc. The pyribole of these dikes is principally augite which shows no staining or alteration along cleavages or around the periphery. The feldspar of the dikes is principally labradorite, occurring in Carlsbad twins that show only the slightest amount of cloudiness due to incipient sericitization.

No brown hornblende has been found in any of the thin sections. Therefore the writer cannot agree with Merrill (1892, p. 49) who classed them as camptonites. Analysis 11 of table 3 shows a typical camptonite. Analysis 12, in the same table, is of a dike in marble in the Lewiston quarry, and analysis 13 is of a dike that cuts the Taylor Brook gneiss. Slight differences in chemical composition might be ascribed to differences in the host rock.

Contact effects.—A baked or chilled contact, a weathered zone of varying width, or a slight discoloration of the marble appear to be the only effect that the basic dikes have exerted on the marbles of the area. A comparison of analyses 4, 12, and 1 in Table 4 shows differences in the amounts of silica, alumina, and iron in the marble beds cut by basic dikes.

A thin section study of specimens from dike number 4 contact (represented by analysis 4, Table 4) shows that the color of the groundmass of the dike changes perceptibly and abruptly from dark yellowish brown at the contact to pale yellow 1.8 millimeters from the contact. None of the feldspar laths in the dike at the contact is more than 15 degrees from parallelism with the contact. With increasing distance from the contact labradorite laths are shorter but more abundant. Several small grains of scapolite and calcite are embedded in the dike groundmass. Magnetite is less abundant away from the contact and seems to be localized around almost completely serpentinized olivines. A few scattered, unaltered hornblendes (extinction 11°) occur. Calcite and diopside, prominent on the marble side of the contact, occur sporadically in the dike groundmass.

BASIC SILLS

The writer knows of no basic sills in the area. The nearest approach to sill-like characteristics in basic rocks is a 5-foot dike which cuts the pegmatite and lime-silicate gneiss of the Androscoggin formation in the Androscoggin River at Lewiston (Fig. 10, E).

The occurrence of amphibolite in the Pejepscot gneiss at Parson's Mill might be regarded by some as a metamorphosed sill, but the writer has already advanced arguments to account for a sedimentary origin of this amphibolite.

AGE OF THE IGNEOUS ROCKS

The preliminary geologic map of Maine (Fig. 2) prepared by Keith in 1933 shows granites and other igneous rocks of three different ages in southwestern Maine. Most of the igneous rocks described in this paper would fall within the pre-Cambrian classification of Keith. Bastin (1911, p. 15) suggested that all the granites are the same age—late Silurian or Devonian. Gonyer (1937, p. 59) established a Carboniferous age for the pegmatites of the Topsham area on the basis of his study of samarskite from that region. The writer believes that all the granites and pegmatites mapped in the area are late Paleozoic. Fragmentary data from the hornblende gabbro of the Androscoggin Lake region indicate that it is later than the sediments and is either contemporaneous with, or slightly later than, the granites and granodiorites of the same area.

Urry (personal communication) has reported an age of 170 ± 8 million years for freshly blasted dike material from the Lewiston City quarry.

He states that this is the same age as obtained from the dolerite offshoot of the West Rock sill at New Haven, Connecticut. Less fresh material, taken from basic dikes at Mt. Apatite, analysed by Urry gave an age of 155 ± 8 million years. The basic dikes of the Lewiston region are properly placed in the Triassic. They cut the massive igneous rocks and the metamorphosed sedimentary rocks of the region.

SUMMARY STATEMENT

The principal conclusions which have resulted from the study of the Lewiston area are:

(1) The Sabattus, Androscoggin, Taylor Brook, and Pejepscot formations are metamorphosed equivalents of sedimentary rocks that have been contaminated in varying degrees by middle or late Paleozoic acidic intrusions.

(2) These metamorphosed rocks occur in a major synclinal structure in which the intensity of metamorphism decreases from Lewiston northeastward to Waterville.

(3) The Sabattus formation passes from the high-grade zone of metamorphism into the middle-grade zone at Winthrop (Fig. 9, G and L) and into the low-grade chloritic and fossiliferous mid-Silurian slates southwest of Waterville.

(4) At localities A, B, and J in Figure 9, the Sabattus formation rests conformably on interbedded metamorphosed sandstones and shales which, in turn, overlie conformably the Androscoggin lime-silicate gneiss and marble. The same stratigraphic sequence occurs from Sw to Sv on Figure 9.

(5) The heavy line on Figure 9 indicating Keith's south and southwest boundary of the pre-Cambrian can no longer be used since metamorphosed rocks crossed by this line are in the same zone of metamorphism.

(6) The Pejepscot formation shown north of D in Figure 9 has been traced southwestward through Falmouth (loc. H) to the Stevens Quarry (loc. K) in Portland where the outcrops are in the low-grade zone of metamorphism.

(7) There is no evidence of large-scale faulting in the area.

(8) Reconnaissance studies in the area between Dundee Falls (loc. F, Fig. 9), Cornish, and Limerick reveal repetitions of the Sabattus and Androscoggin formations in the middle-grade zone of metamorphism.

(9) No unconformities occur between the Sabattus, Androscoggin, Taylor Brook, and Pejepscot formations.

(10) The supposed differences in ages of the formations in this part of Maine were apparently established because of differences in degree of metamorphism.

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Bates College, Lewiston, Maine
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Project Grant 140-35.

EXPLANATION OF PLATES 6-9

Plate 6.—Photomicrographs of Pejepscot Gneiss and Its Correlatives

Figure

1.—Quartz-feldspar-biotite gneiss; moderately coarse-grained biotite not chloritized; feldspars unaltered (Me. 383). x 26.

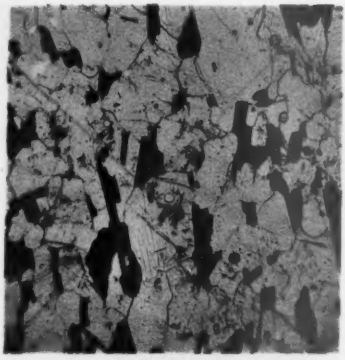
2.—Quartz-feldspar-biotite gneiss; large, yellowish-brown biotite plates well oriented and not chloritized; feldspars fresh. (Me. 347). x 26.

3.—Schist facies of Pejepscot formation. Quartz-biotite-feldspar schist; uneven color of biotite due to slight degree of chloritization (Me. 374). x 26.

4.—Taylor Brook gneiss. Rods of colorless to yellowish-brown biotite are shorter, and feldspars show higher degree of sericitization than in sections of Figures 1, 2, and 3 (Me. 376). x 26.

5.—Amphibolite in Pejepscot formation at Parson's Mill. Reddish-brown biotite, darkest areas; euhedral and subhedral brown hornblende, slightly chloritized; basic plagioclase, areas of low relief (Me. 281). x 26.

6.—Epidote-chlorite schist at Bunganuc Landing. Hornblende, epidote, feldspar (low relief), chlorite (grayish); disseminated biotite (black). (Spring Point greenstone of Katz) (Me. 353). x 26.



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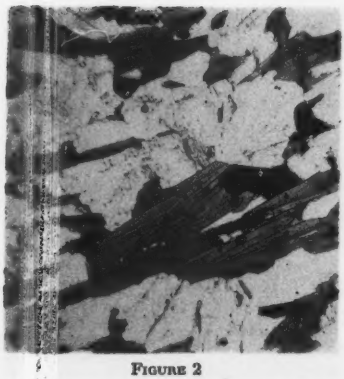

FIGURE 2

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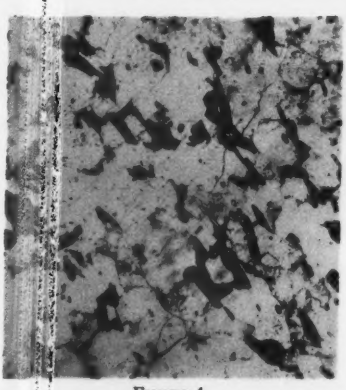

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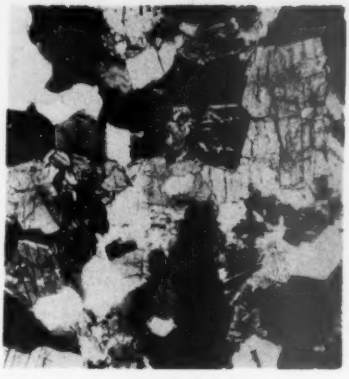

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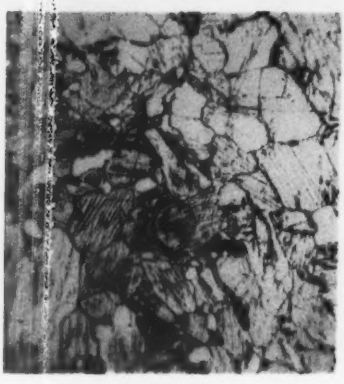


FIGURE 6

PHOTOMICROGRAPHS OF PEJEPSCOT GNEISS AND ITS CORRELATIVES

FIGURE 1

FIGURE 2

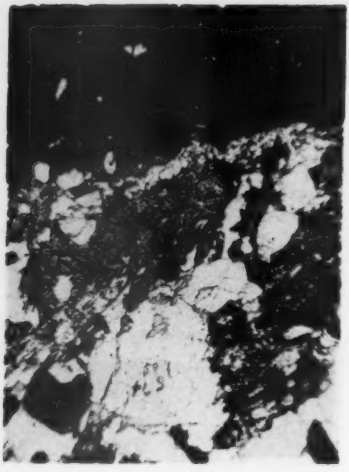


FIGURE 3

FIGURE 4

BASIC DIKES IN CONTACT WITH MARBLE

PLATE 7.—BASIC DIKES IN CONTACT WITH MARBLE

Figure

1.—Dike number 5; 25 inches wide; deeply weathered contact against marble; calcite veins in vertical fracturing; Lewiston City Quarry.

2.—Dike number 7; 30 inches wide; chilled or baked contact against marble; Lewiston City Quarry.

3.—Marble-dike contact. Scapolite, quartz, calcite, near dike contact. High-relief mineral is unchloritized diopside, associated with graphite (black) and calcite. From contact of dike number 7, x 26.

4.—Marble-dike contact. Feldspar and calcite veins in basic dike (upper black). Scapolite, quartz, vesuvianite, and feldspar near contact. Same thin section as Figure 3. x 26.

PLATE 8.—PHOTOMICROGRAPHS OF ANDROSCOGGIN MARBLE AND SABATTUS FORMATION

Figure

1.—Marble at Winthrop. Chiefly small, slightly elongated calcite crystals that show no strain shadows or bent twinning lamellae. Sporadic quartz, biotite, and graphite (Me. 387). x 26.

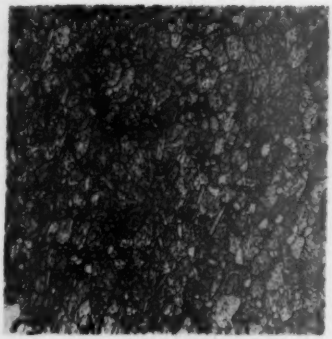
2.—Marble from Androscoggin formation. Well-developed plates of calcite, yellowish to reddish-brown biotite, diopside (left of center), graphite (black), and sphene (below biotite). Lewiston City Quarry (Me. 9). x 26.

3.—Quartz-biotite schist from East Wales. Uniform-grained groundmass of quartz and albite-oligoclase; quartz fractured but unstrained; biotite plates to lower left of quartz vein; crossed nicols (Me. 292). x 26.

4.—Sillimanite schist. Sheafs of sillimanite rods with quartz and biotite (dark to black) (Me. 198). x 26.

5.—Graphite schist. Graphite (black) with slender, clear rods of sillimanite. Note graphite in sillimanite fractures (Me. 204). x 26.

6.—Garnet gneiss. Large unchloritized garnets in quartz groundmass (Me. 392). x 26.



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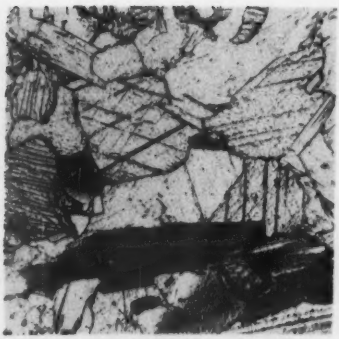

FIGURE 2

FIGURE 3

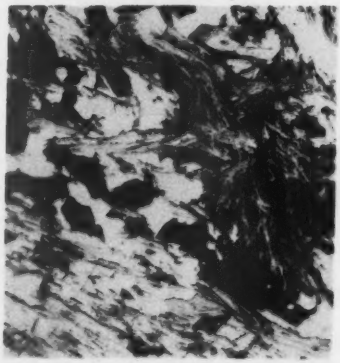

FIGURE 4

FIGURE 5

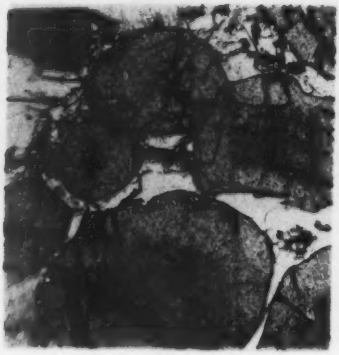

FIGURE 6

PHOTOMICROGRAPHS OF ANDROSCOGGIN MARBLE AND SABATTUS FORMATION

FIGURE 1

FIGURE 2

FIGURE 3

FIGURE 4

PHOTOMICROGRAPHS OF SABATTUS AND ANDROSCOGGIN FORMATIONS

PLATE 9.—PHOTOMICROGRAPHS OF SABATTUS AND ANDROSCOGGIN FORMATIONS

Figure

1.—Lime-silicate gneiss, Androscoggin formation. Euhedral to subhedral diopside, sphene (nearly black), with calcite, quartz, feldspar, and biotite (Me. 162). x 33.

2.—Transitional beds. Upper half: quartz, albite-oligoclase, colorless to pale yellow-brown biotite, flakes and veins of graphite; lower half: diopside, clinozoisite, calcite, with abundant graphite (Me. 262). x 26.

3.—Quartz-biotite schist of Androscoggin formation near Tacoma Lakes. From specimens obtained in beds shown in Figure 1 of Plate 5; crossed nicols (Me. 182). x 26.

4.—Sillimanite schist, Sabattus formation. Cluster of sillimanite crystals sheathed by muscovite with biotite, quartz, and muscovite border. From near East Wales (Pl. 1). x 26.